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Allelopathic interactions between the HAB dinoflagellate *Ostreopsis cf. ovata* and macroalgae.

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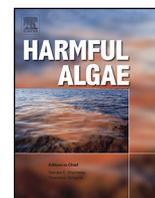
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## Harmful Algae

journal homepage: [www.elsevier.com/locate/hal](http://www.elsevier.com/locate/hal)Allelopathic interactions between the HAB dinoflagellate *Ostreopsis* cf. *ovata* and macroalgaeQ1 Stefano Accoroni<sup>a,\*</sup>, Isabella Percopo<sup>a,1</sup>, Federica Cerino<sup>a,2</sup>, Tiziana Romagnoli<sup>a</sup>,  
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## ABSTRACT

Intense blooms of the toxic benthic dinoflagellate *Ostreopsis* cf. *ovata* have been a recurrent phenomenon along several Mediterranean coasts during summer in the last few years. These blooms are often associated with noxious effects on humans and deaths of benthic invertebrates. Previous studies carried out on the Conero Riviera (northern Adriatic Sea) highlighted that *Ostreopsis* abundances recorded on rocks were significantly higher than on the surface of seaweeds, suggesting that some allelopathic interactions might occur between *Ostreopsis* and macroalgal substrates. In this study we investigated under experimental conditions the interactions between *O. cf. ovata* and three of the most common macroalgae in this area: *Dictyota dichotoma* (brown alga), *Rhodomyenia pseudopalmata* (red alga) and *Ulva rigida* (green alga). Three different experiments were set up: *O. cf. ovata* was grown (i) together with fresh macroalgal tissues, (ii) in media in which macroalgae were previously cultured, and (iii) in media with the addition of dry macroalgal powder at different concentrations. The results indicated that all the investigated seaweeds exerted negative effects toward the benthic dinoflagellate *O. cf. ovata*. *D. dichotoma* inhibited the growth of *O. cf. ovata* in all tested experimental conditions; *U. rigida* had inhibitory effect both in form of fresh thalli and dry powder but not as growth medium filtrate, suggesting that either *Ulva* does not release any allelopathic compound in the medium in absence of *O. cf. ovata* or the alleged released allelochemicals are rapidly degradable. Neither the fresh thalli of *R. pseudopalmata* or the filtrate of its culture medium showed any inhibitory effects, while a negative effect was only observed at high concentrations of dry thallus powder. With the exception of *D. dichotoma* co-culture experiment, a complete algicidal effect was never observed partly because *O. cf. ovata* produced a large amount of resting stages, which permitted its survival.

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## 1. Introduction

Q2 In the last decade, blooms of the toxic benthic dinoflagellate *Ostreopsis* cf. *ovata* Fukuyo have been a recurrent phenomenon along several Mediterranean coastal areas during summer (Vila et al., 2001; Turki, 2005; Aligizaki and Nikolaidis, 2006; Mangialajo et al., 2008, 2011; Totti et al., 2010; Amzil et al., 2012; Illoul et al.,2012; Ismael and Halim, 2012; Pfannkuchen et al., 2012; Casabianca et al., 2014). In these areas, *O. cf. ovata* is well-known for its toxin production, including both palytoxin-like compounds (isobaric palytoxin and ovatoxin-a, b, c, d, e, f and g) and mscarenotoxin-a and c (Rossi et al., 2010; Ciminiello et al., 2011, 2012; Scalco et al., 2012; Uchida et al., 2013; García-Altare et al., 2015) that cause both mortality of benthic marine organisms (Shears and Ross, 2009; Accoroni et al., 2011; Gorbi et al., 2012, 2013; Pagliara and Caroppo, 2012) and noxious effects on human health (Gallitelli et al., 2005; Kermarec et al., 2008; Tichadou et al., 2010; Del Favero et al., 2012).

Several studies have been conducted to assess the role of abiotic factors (mainly hydrodynamics, water temperature and nutrients) on the blooms dynamics (Chang et al., 2000; Vila et al., 2001; Monti et al., 2007; Shears and Ross, 2009; Totti et al., 2010; Accoroni et al.,

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2012a,b, 2015; Mabrouk et al., 2011; Mangialajo et al., 2011; Selina et al., 2014), while biotic factors such as allelopathic interactions between *Ostreopsis* and other organisms have only been partially addressed. The allelopathic interactions have been well documented among toxic dinoflagellates and co-occurring microalgae under unfavorable environmental conditions (Fistarol et al., 2003, 2004; Granéli and Johansson, 2003; Granéli and Hansen, 2006; Prince et al., 2008), and Monti and Cecchin (2012) showed that *O. cf. ovata* had a weak allelopathic activity toward other benthic dinoflagellates as well. However, to the best of our knowledge, allelopathic interactions between *Ostreopsis* and macroalgae have never been considered. *O. cf. ovata* commonly grows over all benthic substrata (rocks, pebbles, seaweed thalli, mollusc shells, etc.), and during periods of intense proliferation produces a conspicuous brownish mat which is only loosely attached to the substrata. Previous studies on the Conero Riviera, where *O. cf. ovata* blooms reach abundances among the highest of the entire Mediterranean coasts (Mangialajo et al., 2011), highlighted that *Ostreopsis* abundances on rocks were significantly higher than those recorded on seaweeds suggesting that some allelopathic interactions might occur between *Ostreopsis* and its macroalgal hosts (Totti et al., 2010).

Algal-bloom control is an important issue for the protection of the water environment due to the negative impacts on human economy and health, especially when the involved bloom-forming species are toxic. Moreover, the development of environment-friendly and cost-effective strategies for controlling algal blooms, such as using the allelopathy of aquatic macrophytes has gained great interest and has been suggested by several authors (Jeong et al., 2000; Nan et al., 2004; Jin et al., 2005; Wang et al., 2007a,b; Hu and Hong, 2008; Tang and Gobler, 2011). The interactions between microalgae and macroalgae have been investigated between phytoplankton species that form blooms and a number of both freshwater (Gross, 2003; Hu and Hong, 2008) and seawater macrophytes (Gross, 2003; Jin and Dong, 2003; Nan et al., 2004, 2008; Jin et al., 2005; Wang et al., 2007a,b; Ye and Zhang, 2013) but no information is available about macroalgae and benthic dinoflagellate interactions.

In this study, we investigated the interactions between *Ostreopsis cf. ovata* and three macroalgal species under laboratory conditions. The macroalgae were chosen among the most common species on the Conero Riviera during the bloom period of *Ostreopsis*: *Dictyota dichotoma* (Hudson) J.V. Lamouroux (brown alga), *Rhodomenia pseudopalmata* (J.V. Lamouroux) P.C. Silva (red alga) and *Ulva rigida* C. Agardh (green alga). Three different experiments were carried out: *O. cf. ovata* was grown (i) together with fresh macroalgal tissues, (ii) in filtered culture media in which macroalgae were previously grown, and (iii) in media with addition of dry macroalgal powder at different concentrations.

## 2. Materials and methods

### 2.1. *Ostreopsis cf. ovata* cultures

A strain of *Ostreopsis cf. ovata* was isolated by the capillary pipette method (Hoshaw and Rosowski, 1973) from seawater samples collected from the bloom that occurred on the Conero Riviera (N Adriatic Sea) in summer 2007 (strain OoAPn0807/E). After initial growth in microplates, cells were cultured at  $21 \pm 0.1$  °C under a 12:12 h L:D cycle and an irradiance of  $90\text{--}100 \mu\text{mol m}^{-2} \text{s}^{-1}$ , in modified f/4 medium prepared by adding macronutrients at a f/4 medium concentration without silica (Guillard and Rytner, 1962) and selenium to filtered and autoclaved natural seawater (salinity 35). Trace metals, iron, vitamins (H, B1 and B12) and HEPES pH 7.1 were added at levels corresponding to f/2 medium. The same physico-chemical conditions were used in all

experiments described below, with the addition of germanium dioxide ( $6 \text{ mg l}^{-1}$ ), when specified, to prevent the growth of diatoms.

Microalgae were cultured to the exponential phase before inoculation in the following experiments. All the experiments were carried out in three replicates.

### 2.2. Macroalgal sampling and pre-treatment

Thalli of three macroalgal species, i.e., *Dictyota dichotoma*, *Rhodomenia pseudopalmata* and *Ulva rigida*, were collected on the Conero Riviera in summer 2009 and treated to remove the epiphytes from their surface as follows: they were washed carefully in filtered sea water (FSW) containing 1% of surfactant, rinsed in FSW and then observed at a stereo-microscope in order to mechanically remove the epiphytes with scalpels and tweezers; afterwards, a 3-min dip in tap water followed by a washing with chloramphenicol (50 ppm in FSW) led to the complete removal of residual epiphytic cells and bacteria respectively. After rinsing in FSW, macroalgal thalli were cut into fragments of approximately  $9 \text{ cm}^2$  and acclimated for one week in FSW (containing  $6 \text{ mg l}^{-1}$  germanium dioxide).

### 2.3. Co-cultures of *Ostreopsis cf. ovata* and fresh macroalgal thalli

The co-cultures were set up with 1 g of thallus segments of each tested seaweed in 500 ml of medium containing germanium dioxide. For each species, 3 flasks were inoculated with  $100 \text{ cells ml}^{-1}$  of *O. cf. ovata*, and 3 flasks containing  $100 \text{ cells ml}^{-1}$  of *Ostreopsis cf. ovata* without macroalgal thalli were used as control. The flasks were incubated for 20 days in a culture chamber at the conditions previously described. Every 2 days, 3 aliquots (2 ml) were taken from each flask (after gentle shaking of each thallus with a pair of tweezers and a homogenization of the medium) and preserved with Lugol's solution in the dark to assess the cell densities, and 1 aliquot (4 ml) was filtered (GF/F Whatman, diameter 25 mm, nominal pore size  $0.7 \mu\text{m}$ ) and stored in polyethylene bottles at  $-22$  °C for nutrient analysis. Every 7 days, pH was checked and adjusted to maintain it to value of 8 until the end of the experiment.

### 2.4. Cultures of *Ostreopsis cf. ovata* in macroalgal culture medium filtrate

For each macroalgal species, 24 g of thallus segments pre-treated as above were maintained in 1 l FSW for one week. Afterwards, macroalgal thalli were removed and the culture medium was filtered ( $0.22 \mu\text{m}$  pore size) and used to prepare the medium for the experiment: the pH was adjusted to 8 and the nutrients were added to obtain a modified f/4 medium as described previously. Culture flasks containing 250 ml of medium were inoculated with *Ostreopsis cf. ovata* cells to obtain a final concentration of  $500 \text{ cells ml}^{-1}$ . As a control,  $500 \text{ cells ml}^{-1}$  of *O. cf. ovata* were inoculated in fresh modified f/4 medium. Subsamples (2 ml) were sampled every 2–3 days for 23 days and fixed with Lugol's solution.

### 2.5. Cultures with dry powder of macroalgae

Fresh thalli of each macroalga were dried at room temperature and pulverized using a mortar and a pestle. Different amounts of dry powder ( $0.4, 0.8, 1.6 \text{ g l}^{-1}$ ) were added to flasks containing *Ostreopsis* cultures ( $500 \text{ cells ml}^{-1}$ ) in 300 ml modified f/4 medium. Microalgal cultures without addition of dry macroalgal powder were used as controls. Cultures were maintained for 18 days during which subsamples (2 ml) were taken every 2 days and fixed with Lugol's solution.

## 2.6. Microscope counting

Densities of *Ostreopsis cf. ovata* were estimated after homogenization using either Utermöhl (Edler and Elbrachter, 2010) or Sedgewick-Rafter (Guillard, 1978) chambers, through an inverted light microscope (Zeiss Axiovert 135) and a light microscope (Zeiss Axioskop) respectively, both equipped with phase contrast, at 200× magnification. Counting was performed on 10–30 random fields, 1–2 transects, or the whole chamber, in order to count a representative cell number. Total densities (vegetative cells and cysts) were expressed as cells ml<sup>-1</sup>.

## 2.7. Cyst isolation for germination tests

Cysts of *Ostreopsis cf. ovata* were isolated at the end of the experiments and used to perform germination tests. Single cysts were isolated by the capillary pipette method according to the classical methodology (Hoshaw and Rosowski, 1973) and put separately in 24-well culture plates filled with fresh growth medium. Plates were placed in the culture chamber in the conditions previously described and were observed every day for 8 weeks.

## 2.8. Nutrient analysis

Nutrient variation during the co-cultures of *Ostreopsis cf. ovata* with fresh thalli was monitored throughout the experiment. Analyses of NO<sub>3</sub><sup>-</sup>, NO<sub>2</sub><sup>-</sup>, NH<sub>4</sub><sup>+</sup>, and PO<sub>4</sub><sup>3-</sup> were conducted following the colorimetric method by Strickland and Parsons (1968), adapted for an Autoanalyzer QuAatro Axflow. Limits of detection were 0.02 μmol l<sup>-1</sup> for NO<sub>3</sub><sup>-</sup> and NO<sub>2</sub>, and 0.03 μmol l<sup>-1</sup> for PO<sub>4</sub><sup>3-</sup>.

## 2.9. Calculations and statistical analyses

The microalgal growth was expressed as specific growth rate ( $\mu$ ) using the equation

$$\mu = \frac{(\ln N_1 - \ln N_0)}{T}$$

where  $N_1$  is the final density,  $N_0$  is the initial density, and  $T$  is the number of days between two measurements.

Differences in final cell densities of *Ostreopsis cf. ovata* in each experiment (i.e., co-cultures, macroalgal filtrate and dry macroalgal powder) between the three different macroalgal species were assessed through a one-way analysis of variance (ANOVA). Moreover, in the co-culture experiment, differences in nutrient concentrations between the three different macroalgae were assessed through an ANOVA test as well. When significant differences for the main effect were observed ( $p < 0.05$ ), a Tukey's pairwise comparison test was also performed. The statistical analyses were conducted using Statistica (StatSoft Inc., Tulsa, OK, USA) software.

## 3. Results

### 3.1. Co-cultures of *Ostreopsis cf. ovata* with fresh macroalgal thalli

The first general observation regarding the pattern of colonization in each flask is that *Ostreopsis cf. ovata* cells colonized the bottom of the flask rather than macroalgal thalli. Our results showed that *O. cf. ovata* growth was markedly affected only by the presence of two macroalgal species, i.e., *Dictyota dichotoma* and *Ulva rigida*: at the end of the experiment (day 20) *Ostreopsis* cell abundance in co-culture with *D. dichotoma* and *U. rigida* was reduced by 100% and 94% respectively, compared to the day of the

inoculum (Fig. 1). The density of *O. cf. ovata* was significantly lower with *D. dichotoma* ( $0.08 \pm 0.06$  cells ml<sup>-1</sup>) and *U. rigida* ( $31.6 \pm 4.6$  cells ml<sup>-1</sup>) than with *Rhodymenia pseudopalmeta* ( $823.2 \pm 59.8$  cells ml<sup>-1</sup>,  $p < 0.001$ ) and in the control ( $735.4 \pm 125.1$  cells ml<sup>-1</sup>,  $p < 0.001$ ). The average lethal times (LT50), which represents the time at which 50% of the *Ostreopsis* cells were dead, in co-cultures with *U. rigida* and *D. dichotoma* were 12 and 8 days, respectively. On the contrary, the growth of *O. cf. ovata* was not inhibited by the presence of *R. pseudopalmeta*, as no significant difference was observed between the maximum yield of *O. cf. ovata* in *R. pseudopalmeta* co-culture and the control. The maximum yield was reached at the day 18 with  $1535 \pm 538$  cells ml<sup>-1</sup> in the control and  $1016 \pm 210$  cells ml<sup>-1</sup> in the *R. pseudopalmeta* co-culture. The growth rate of *Ostreopsis* in *R. pseudopalmeta* co-culture was comparable with that of the control (0.17 and 0.19 day<sup>-1</sup> respectively).

Regarding the nutrient concentrations during the entire experiment (Fig. 2), we considered the phosphate (PO<sub>4</sub><sup>3-</sup>) and the dissolved inorganic nitrogen (DIN) as a sum of nitrates, nitrites and ammonia. A marked decrease of DIN throughout the experiment was observed in *Rhodymenia pseudopalmeta* and *Ulva rigida* co-cultures, while PO<sub>4</sub><sup>3-</sup> concentration did not show appreciable variation.

Comparing nutrient content in different co-cultures, significantly higher values of both DIN and PO<sub>4</sub><sup>3-</sup> were observed in *Dictyota dichotoma* co-culture than in *Rhodymenia pseudopalmeta* and *Ulva rigida* ( $p < 0.001$ , Table 1). Comparing *U. rigida* and *R. pseudopalmeta* co-cultures, PO<sub>4</sub><sup>3-</sup> was significantly higher in the former than in the latter ( $p < 0.05$ , Table 1), while no significant differences were observed in DIN concentrations.

### 3.2. Cultures of *Ostreopsis cf. ovata* in macroalgal culture medium filtrate

Among the macroalgae tested, only *Dictyota dichotoma* culture filtrate exhibited inhibiting effects on *Ostreopsis cf. ovata* growth: *Ostreopsis* cell numbers immediately decreased (LT50 = 2) (Fig. 3). At the end of the experiment (day 23), the cell density of *O. cf. ovata* was significantly lower in the culture filtrate of *D. dichotoma* than in those of *Rhodymenia pseudopalmeta* ( $p < 0.001$ ), *Ulva rigida* ( $p < 0.001$ ) and control ( $p < 0.001$ , Table 2). It is noteworthy that since the second sampling day in *D. dichotoma* treatment we observed the appearance of cysts (both thin and double-walled cysts, Fig. 4B and C). The percent abundances of double-walled cysts increased toward the end of the experiment, becoming the predominant morphotype observed in the final day of the experiment.

On the contrary, in filtrates of *Ulva rigida* and *Rhodymenia pseudopalmeta* the *Ostreopsis* maximum yield was significantly

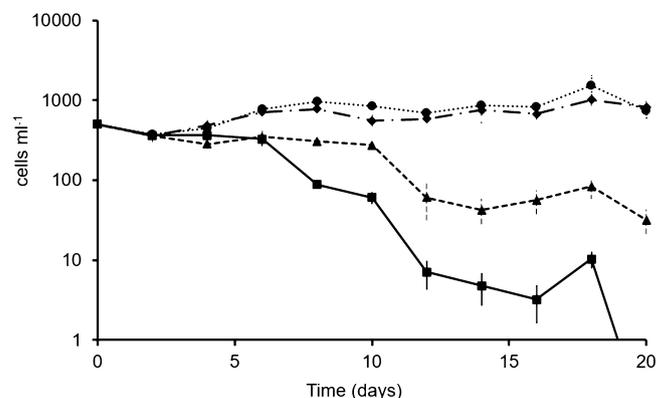
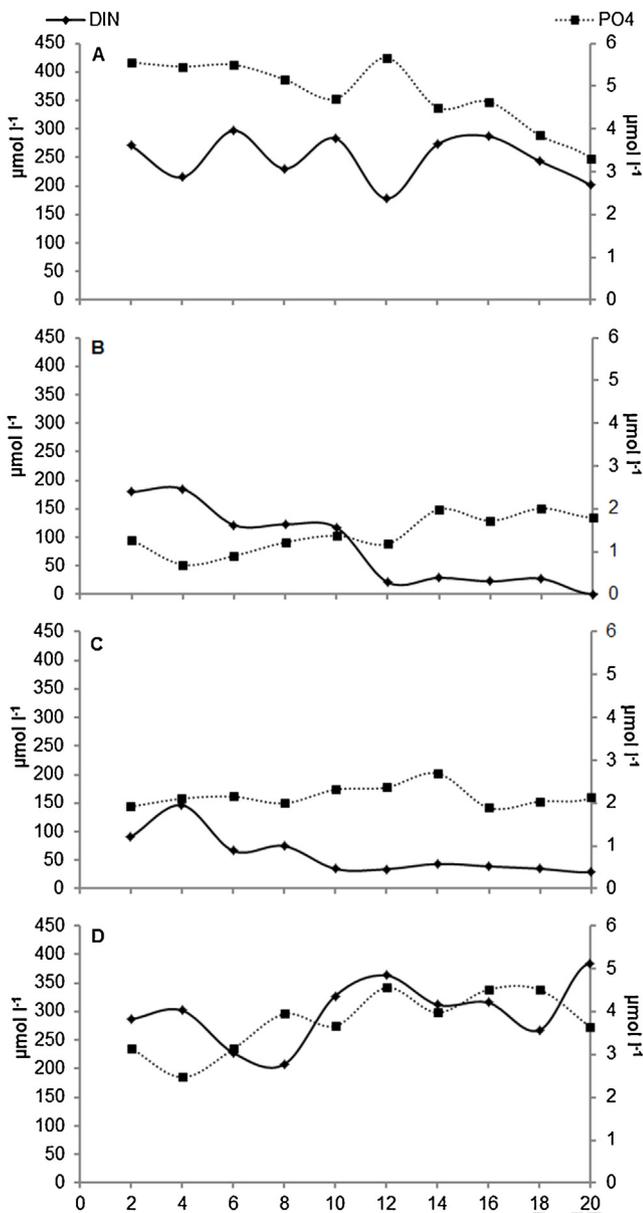


Fig. 1. Growth pattern of *Ostreopsis cf. ovata* cells growing in co-culture with fresh thalli of (■) *Dictyota dichotoma*, (◆) *Rhodymenia pseudopalmeta*, (▲) *Ulva rigida* and (●) control. Bars indicate standard deviation.

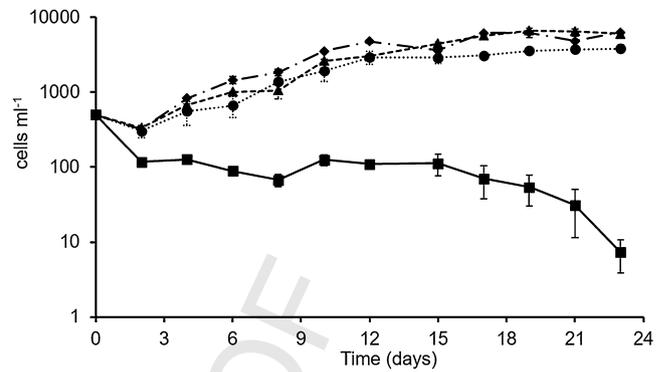


**Fig. 2.** Temporal variability of nutrient concentration ( $\mu\text{mol l}^{-1}$ ) in cultures of *Ostreopsis cf. ovata* (A) without macroalgal thalli (control) and in co-culture with fresh thalli of (B) *Rhodymenia pseudopalmeta*, (C) *Ulva rigida* and (D) *Dictyota dichotoma*. Dissolved inorganic nitrogen (DIN, left y-axis) and phosphate ( $\text{PO}_4^{3-}$ , right y-axis).

higher than in the control ( $p < 0.001$ , Table 2) and the growth rates,  $0.28$  and  $0.38 \text{ day}^{-1}$  respectively, were higher than for the control ( $0.25 \text{ day}^{-1}$ ). In the filtrate of *R. pseudopalmeta*, maximum value was recorded in the final sampling day, while in the filtrate of *U. rigida* was recorded on day 19 ( $6597 \pm 515 \text{ cells ml}^{-1}$ ).

### 3.3. Cultures with dry powder of macroalgae

The results of this experiment showed that all the macroalgal species exhibited an inhibitory effect on cultures of *Ostreopsis cf. ovata* (Fig. 5) as all the powder concentrations tested led to significantly lower values of cell densities at the end of the experiment compared to the control ( $p < 0.001$ , Table 3), except for the powder of *Rhodymenia pseudopalmeta* at the lowest concentration ( $0.4 \text{ g l}^{-1}$ ) which allowed the growth of *O. cf. ovata* (growth rate =  $0.19 \text{ day}^{-1}$ ).



**Fig. 3.** Growth pattern of *Ostreopsis cf. ovata* cells growing with macroalga culture medium filtrates of (■) *Dictyota dichotoma*, (◆) *Rhodymenia pseudopalmeta* and (▲) *Ulva rigida* and (●) control. Bars indicate standard deviation.

Generally, the trend of total densities throughout the experiment showed a gradual decrease. At the end of the experiment (day 18), the abundance of *Ostreopsis* was reduced to values between 59 and 79% respect to the inoculum for powder of *Dictyota dichotoma* (LT50 of 10, 16 and 4 for  $0.4$ ,  $0.8$  and  $1.6 \text{ g l}^{-1}$  respectively), of 17–37% for powder of *Ulva rigida* (at all the powder concentrations tested), while for powder of *Rhodymenia pseudopalmeta* such decrease was observed only at concentrations higher than  $0.4 \text{ g l}^{-1}$  (i.e., 19% for  $0.8 \text{ g l}^{-1}$  and 52% for  $1.6 \text{ g l}^{-1}$ , LT50 = 18, Fig. 5). In all experiments (except for powder of *R. pseudopalmeta* at concentration  $0.4 \text{ g l}^{-1}$ ) vegetative cells were replaced by cysts: both thin and double-walled cysts were observed with an increase of percent abundances of the latter toward the end of the experiment.

### 3.4. Germination tests

Thin and double-walled cysts isolated at the end of the experiments (see above) were put in favorable conditions (fresh replete medium,  $21 \text{ }^\circ\text{C}$ ) to stimulate the germination. Among them, only thin-walled cysts germinated producing vegetative cells in a short time interval (3 h–2 d), while double-walled cysts did not germinate. The estimated percentage of germination of thin walled cysts was around 60%.

## 4. Discussion

The results obtained in this study highlighted negative interactions that occurred between the benthic dinoflagellate *Ostreopsis cf. ovata* and the macroalgae *Dictyota dichotoma* (brown alga), *Rhodymenia pseudopalmeta* (red alga) and *Ulva rigida* (green alga): *D. dichotoma* and *U. rigida* showed an evident inhibitory effect, while such effect was not observed for *R. pseudopalmeta* except that at high concentrations of dry macroalgal powder. The inhibitory effect of macroalgae toward microalgae has been investigated previously and could be interpreted as due to various factors including nutrient and light competition, pH changes and secondary metabolites (allelochemicals) production. Microalgae and macroalgae are known to have an antagonistic relationship in both natural and experimental aquatic ecosystems (Lee and Olsen, 1985; Fong et al., 1993). Firstly, they compete for the nutrients. Pedersen and Borum (1996) analyzed the nitrogen storage and nitrogen-dependent growth rates of microalgae and macroalgae and suggested that microalgae would be superior at high nutrient availability, while at low nutrient availability slow-growing macroalgae would be more successful. Nevertheless, it has been observed in field studies that microalgae are sometimes suppressed by macroalgae at high nutrient availability (Smith and

**Table 1**

Results of ANOVA and Tukey's test about the concentrations of nutrient levels in the co-cultures of *Ostreopsis cf. ovata* with fresh thalli. Mean concentration ( $\mu\text{mol l}^{-1}$ )  $\pm$  standard error (SE) of dissolved inorganic nitrogen (DIN) and  $\text{PO}_4^{3-}$  in the entire experiment and in the control are reported.

|                    | <i>Dictyota dichotoma</i><br>( $\mu\text{mol l}^{-1}$ ) | <i>Ulva rigida</i><br>( $\mu\text{mol l}^{-1}$ ) | <i>Rhododymenia pseudopalmeta</i><br>( $\mu\text{mol l}^{-1}$ ) | Control<br>( $\mu\text{mol l}^{-1}$ ) | p-level                             | Tukey test  |
|--------------------|---|--|---|---------------------------------------|-------------------------------------|---|
|                    | Avg $\pm$ SE  | Avg $\pm$ SE                                     | Avg $\pm$ SE  | Avg $\pm$ SE                          |                                     |   |
| DIN                | 299.23 $\pm$ 17.37                                      | 59.45 $\pm$ 11.65                                | 82.80 $\pm$ 22.15   | 248.13 $\pm$ 12.83                    | ***<br>***<br>***<br>***            | Control > <i>Rhododymenia pseudopalmeta</i><br>Control > <i>Ulva rigida</i><br><i>Dictyota dichotoma</i> > <i>Rhododymenia pseudopalmeta</i><br><i>Dictyota dichotoma</i> > <i>Ulva rigida</i>  |
| $\text{PO}_4^{3-}$ | 3.7522 $\pm$ 0.2191                                     | 2.16080 $\pm$ 0.0769                             | 1.4193 $\pm$ 0.1424   | 4.838 $\pm$ 0.2495                    | **<br>***<br>***<br>***<br>***<br>* | Control > <i>Dictyota dichotoma</i><br>Control > <i>Rhododymenia pseudopalmeta</i><br>Control > <i>Ulva rigida</i><br><i>Dictyota dichotoma</i> > <i>Rhododymenia pseudopalmeta</i><br><i>Dictyota dichotoma</i> > <i>Ulva rigida</i><br><i>Ulva rigida</i> > <i>Rhododymenia pseudopalmeta</i> |

\*  $p < 0.05$ .\*\*  $p < 0.01$ .\*\*\*  $p < 0.001$ .

310 Horne, 1988; Sfriso et al., 1989; Sfriso and Pavoni, 1994). Although  
311 a high rate of nutrient uptake has been reported particularly for  
312 *Ulva* species (see e.g., Zertuche-González et al., 2009; Luo et al.,  
313 2012), we excluded the hypothesis that the inhibitory effect  
314 observed in the co-culture experiments was due to nutrient  
315 competition, as nutrient levels in both *D. dichotoma* and *U. rigida*  
316 co-cultures showed values comparable to those of the control and  
317 even higher than those in co-cultures of *R. pseudopalmeta* where no  
318 inhibition was observed. Changing in pH in surrounding medium  
319 due to macroalgae growth is a common event, as high rates of  
320 photosynthesis may drawdown  $\text{CO}_2$ , increasing pH levels and  
321 making the environment unsuitable for microalgal growth (Gold-  
322 man et al., 1982; Taraldsvik and Mykkestad, 2000). In this regard,  
323 during our experiments the pH was maintained at values of 8, in  
324 order to prevent that the effect of an increased pH masking  
325 possible allelopathic interactions (Keating, 1977; Schmidt and  
326 Hansen, 2001; Granéli et al., 2008). Finally, macroalgae and  
327 microalgae strongly interact through release of allelopathic  
328 substances and these chemical interactions may suggest interest-  
329 ing opportunities to obtain algicidal products which may be used  
330 in the bloom control (Nan et al., 2004; Hu and Hong, 2008; Tang  
331 and Gobler, 2011). Although in this study chemical analyses were  
332 unfortunately not performed, we can hypothesize that such  
333 interactions likely occurred. Among the macroalgae tested, *D.*  
334 *dichotoma* inhibited the growth of *O. cf. ovata* in all tested  
335 conditions. In particular, the experiment with macroalgal powder  
336 and macroalgal filtrate medium suggests that *D. dichotoma* could  
337 contain/release, irrespective of the presence of microalgae, some  
338 molecules able to exert an inhibitory effect on *Ostreopsis* growth.  
339 Species belonging to the genus *Dictyota* are known to produce  
340 secondary metabolites, i.e., hundreds of terpenes (Cronin et al.,  
341 1997; Vallim et al., 2005), with ecological functions including

defense against feeding by generalist marine herbivores (Paul et al., 342  
2001; Paul and Ritson-Williams, 2008). In addition, brown algae 343  
are well-known for the production of other secondary metabolites, 344  
the phlorotannins, which are considered to be an important 345  
chemical defence against marine herbivores, as well as epiphytes 346  
(Jennings and Steinberg, 1997; Amsler and Fairhead, 2005; Iken 347  
et al., 2009) and have been shown to exert negative effects also on 348  
several red tide microalgae (Nagayama et al., 2003; Wang et al., 349  
2007a). 350

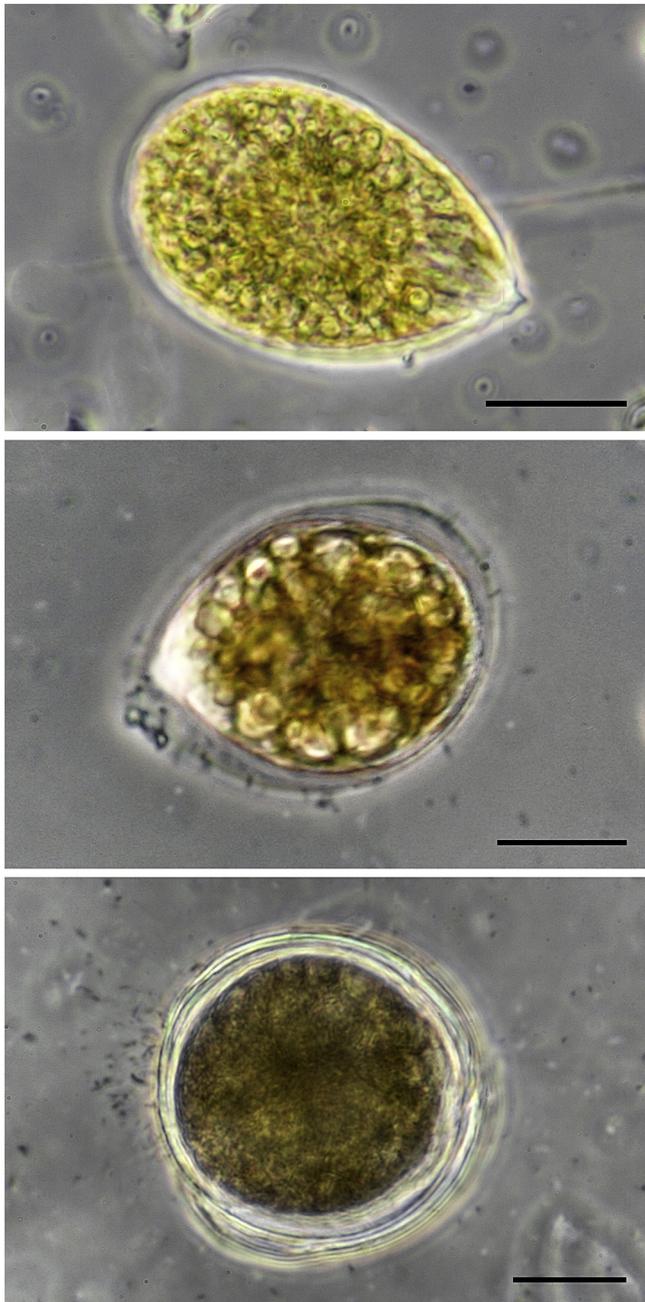
*Ulva rigida* showed a moderate inhibitory effect on *Ostreopsis cf.* 351  
*ovata*, particularly as both fresh thalli and dry powder, while no 352  
inhibition occurred with *U. rigida* growth medium filtrate. This 353  
suggests that either *Ulva* does not release any compound in the 354  
medium in absence of stimulating factors such as microalgae could 355  
represent, or if allelochemicals are released they are rapidly 356  
degraded. Similar results have been obtained by other authors who 357  
hypothesized that the continuous release of small quantities of 358  
rapidly degradable allelochemicals from the fresh tissue of *Ulva* 359  
spp. was essential to inhibit the growth of several microalgae (Jin 360  
and Dong, 2003; Nan et al., 2004, 2008; Jin et al., 2005; Wang et al., 361  
2007a). Tang and Gobler (2011) suggested that the polyunsaturat- 362  
ed fatty acids produced by *Ulva* species (Alamsjah et al., 2005, 363  
2008) probably act as allelochemicals, explaining the inhibitory 364  
effect of *Ulva* on several planktonic HAB species. Other authors 365  
(e.g., Wang et al., 2007b) observed that the culture filtrate of *Ulva* 366  
can exert contrasting species-specific allelopathic interactions on 367  
different bloom-forming dinoflagellates, i.e., both inhibitory (on 368  
*Prorocentrum donghaiense*, *Alexandrium tamarensense* and *Scrippsiella* 369  
*trochoidea*) and stimulatory (on *Amphidinium carterae*) effects. Our 370  
results show a stimulatory effect of culture filtrates of both *U. rigida* 371  
and *Rhododymenia pseudopalmeta* on *Ostreopsis* growth as well, 372  
suggesting that in absence of *O. cf. ovata* they could release some 373

**Table 2**

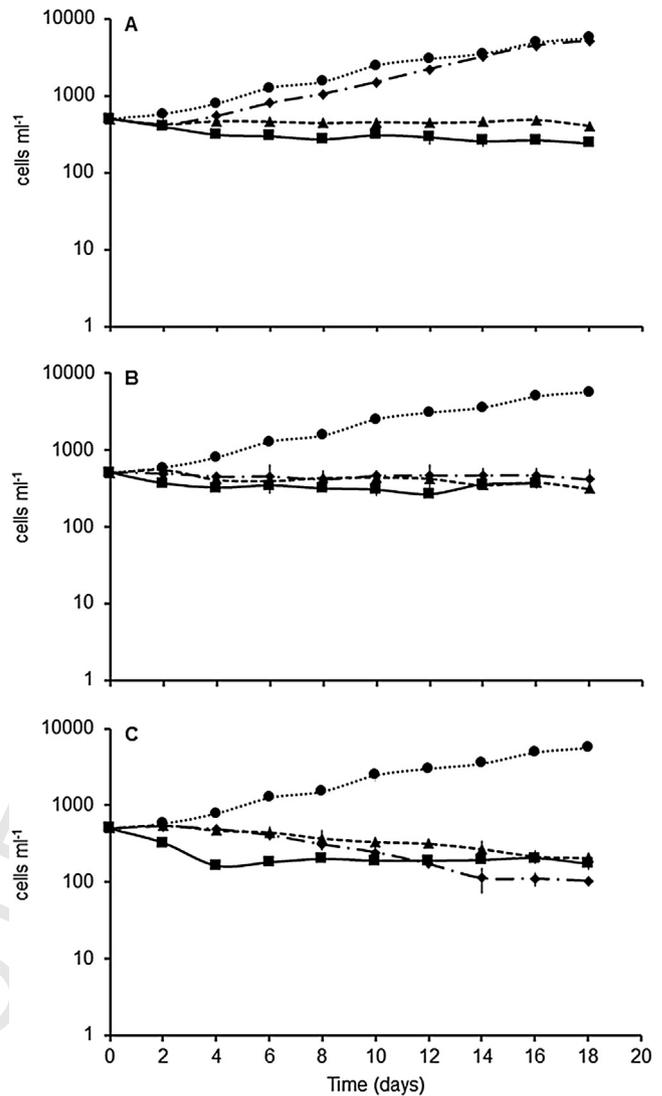
Results of ANOVA and Tukey's test about the mean cell abundances (cells  $\text{ml}^{-1}$ )  $\pm$  standard error (SE) of *Ostreopsis cf. ovata* at the day 23 in the experiment with macroalga culture medium filtrate and in the control.

| <i>Dictyota dichotoma</i><br>cells $\text{ml}^{-1}$ | <i>Ulva rigida</i><br>cells $\text{ml}^{-1}$ | <i>Rhododymenia pseudopalmeta</i><br>cells $\text{ml}^{-1}$ | Control<br>cells $\text{ml}^{-1}$ | p-level                         | Tukey test  |
|---|--|---|-----------------------------------|---------------------------------|---|
| Avg $\pm$ SE  | Avg $\pm$ SE                                 | Avg $\pm$ SE  | Avg $\pm$ SE                      |                                 |   |
| 7.3 $\pm$ 3.6                                       | 6009.9 $\pm$ 305.06                          | 6283.1 $\pm$ 450.2  | 3823.4 $\pm$ 343.8                | ***<br>***<br>***<br>***<br>*** | <i>Dictyota dichotoma</i> < <i>Rhododymenia pseudopalmeta</i><br><i>Dictyota dichotoma</i> < <i>Ulva rigida</i><br><i>Dictyota dichotoma</i> < Control<br><i>Rhododymenia pseudopalmeta</i> > Control<br><i>Ulva rigida</i> > Control |

\*\*\*  $p < 0.001$ .



**Fig. 4.** Different morphotypes of *Ostreopsis cf. ovata* cells observed during the experiments: (A) vegetative cell, (B) thin- and (C) double-walled cysts. Scale bars = 20 µm.



**Fig. 5.** Growth pattern of *Ostreopsis cf. ovata* cells growing with different concentrations (◆ 0.4, ▲ 0.8, ■ 1.6 g l<sup>-1</sup> and ● control) of dry macroalgal powder of (A) *Rhodymenia pseudopalmeta*, (B) *Ulva rigida* and (C) *Dictyota dichotoma*. Bars indicate standard deviation.

et al., 2000; Wang et al., 2007a,b; Ye and Zhang, 2013). The lower inhibitory effect observed in *Rhodymenia* in this study could partly explain results reported in field studies in both northern Adriatic Sea and North Aegean Sea, where the maximum abundances of

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**Table 3**

Mean cell abundances (cells ml<sup>-1</sup>) ± standard error (SE) of *Ostreopsis cf. ovata* at the day 18 and growth rate (day<sup>-1</sup>) in the experiment with dry macroalgal powder at different concentrations (0.4, 0.8 and 1.6 g l<sup>-1</sup>) and in the control.

| Macroalga                       | Powder concentration<br>g l <sup>-1</sup> | AVG ± SE<br>cells ml <sup>-1</sup> | Growth rate<br>day <sup>-1</sup> |
|---------------------------------|---|------------------------------------|----------------------------------|
| <i>Dictyota dichotoma</i>       | 0.4                                       | 103.7 ± 2.9                        | /                                |
| <i>Dictyota dichotoma</i>       | 0.8                                       | 206.0 ± 7.1                        | /                                |
| <i>Dictyota dichotoma</i>       | 1.6                                       | 172.8 ± 9.9                        | /                                |
| <i>Ulva rigida</i>              | 0.4                                       | 417.3 ± 43.8                       | /                                |
| <i>Ulva rigida</i>              | 0.8                                       | 313.2 ± 16.0                       | /                                |
| <i>Ulva rigida</i>              | 1.6                                       | 369.3 ± 10.2                       | /                                |
| <i>Rhodymenia pseudopalmeta</i> | 0.4                                       | 5184.3 ± 149.8                     | 0.19                             |
| <i>Rhodymenia pseudopalmeta</i> | 0.8                                       | 407.1 ± 11.8                       | /                                |
| <i>Rhodymenia pseudopalmeta</i> | 1.6                                       | 241.6 ± 5.2                        | /                                |
| Control                         |   | 5651.2 ± 152.0                     | 0.25                             |

374 compounds which may operate as growth enhancers, also  
375 considering that the filtrate experiment has been carried out with  
376 high thallus concentrations (12 times higher than in co-culture  
377 experiment).

378 On the contrary, *Rhodymenia pseudopalmeta* showed inhibitory  
379 effects only beyond a threshold level of thallus powder concentra-  
380 tion. Red algae are reported as a source of secondary metabolites  
381 including terpenes, which exhibit a range of activities such as  
382 feeding inhibition for marine herbivores (Sakata et al., 1991;  
383 Kurata et al., 1998) and antialgal effect (König et al., 1999). Our  
384 results might suggest that *Rhodymenia* is not a strong producer of  
385 chemical-deterrents, unlike other red algal species: *Corallina*  
386 *pilulifera*, *Gracilaria lemaneiformis* and *Gracilaria tenuistipitata*  
387 displayed algicidal activity against several harmful algae (Jeong

*O. cf. ovata* were generally recorded on Rhodophyceae (e.g., *Corallina* sp., *Ceramium* spp., *Hypnea musciformis*) rather than on other macroalgal groups (Aligizaki and Nikolaidis, 2006; Totti et al., 2010). So far, this has been explained considering that tridimensional articulate thalli morphotypes (as are the above species) could support higher abundances of epibiotic dinoflagellates than simple filamentous thalli (Vila et al., 2001; Parsons and Preskitt, 2007; Totti et al., 2010), but the results of this study suggest that other factors such as chemical interactions might affect the growth of epiphytic dinoflagellates.

Although the powder of *Ulva rigida*, *Dictyota dichotoma* and *Rhodomenia pseudopalmata* as well as the *D. dichotoma* culture filtrate strongly inhibited the *Ostreopsis* growth, in such conditions a complete algicidal effect was not observed, as the dinoflagellate population suddenly produced a lot of resting stages, and in the last days of the experiment the majority of the population was represented by cysts (thin and double-walled cysts), maintaining the total densities at a stable level and comparable to values of the initial inoculum throughout the entire experiment. Thin-walled and double-walled cysts have been previously observed in *O. cf. ovata* cultures and interpreted as short-term and resting cysts respectively; while thin-walled cysts have been demonstrated to germinate already at 21 °C, the double-walled ones germinated at 25 and not at 21 °C (Accoroni et al., 2014). The cyst formation in presence of macroalgae (both powder and filtrate conditions) indicates that the co-existence of macroalgae represented a stress for *Ostreopsis*, suggesting that some allelochemicals might be produced, although unfortunately in this study we did not make a chemical analysis. The cyst production allowed *Ostreopsis* populations to persist, contrarily to results reported by Nagayama et al. (2003) who found that phlorotannins of the brown macroalgae *Ecklonia kurome* killed the cells of *Karenia mikimotoi* and *Cochlodinium polykrikoides*, firstly causing a loss of motility in the cells, then making the cells become round, expand and burst, suggesting an interaction of phlorotannins with microalgal proteins disturbing the control of osmotic pressure.

In conclusion, our results highlighted that the investigated seaweed species exert negative effects toward the benthic dinoflagellate *Ostreopsis cf. ovata*, inhibiting growth and inducing cyst formation, suggesting that these inhibiting effects could be of allelopathic nature. In order to control and/or mitigate HABs, different physical approaches and chemical ways have been developed (Sugawara et al., 2003; Sun and Choi, 2004; Lee et al., 2008; Chen et al., 2009). Considering our results added to the substantial experimental evidence demonstrating the inhibitory activity of several macroalgae on the growth of HAB species, we think that the use of macroalgae in the prevention, control, and mitigation of HABs represents a potential option which could be taken in account in the coastal management.

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