Elevated CO₂ levels affect the activity of nitrate reductase and carbonic anhydrase in the calcifying rhodophyte Corallina officinalis

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Abstract

The concentration of CO₂ in global surface ocean waters is increasing due to rising atmospheric CO₂ emissions, resulting in lower pH and a lower saturation state of carbonate ions. Such changes in seawater chemistry are expected to impact calcification in calcifying marine organisms. However, other physiological processes related to calcification might also be affected, including enzyme activity. In a mesocosm experiment, macroalgal communities were exposed to three CO₂ concentrations (380, 665, and 1486 µatm) to determine how the activity of two enzymes related to inorganic carbon uptake and nutrient assimilation in Corallina officinalis, an abundant calcifying rhodophyte, will be affected by elevated CO₂ concentrations. The activity of external carbonic anhydrase, an important enzyme functioning in macroalgal carbon-concentrating mechanisms, was inversely related to CO₂ concentration after long-term exposure (12 weeks). Nitrate reductase, the enzyme responsible for reduction of nitrate to nitrite, was stimulated by CO₂ and was highest in algae grown at 665 µatm CO₂. Nitrate and phosphate uptake rates were inversely related to CO₂, while ammonium uptake was unaffected, and the percentage of inorganic carbon in the algal skeleton decreased with increasing CO₂. The results indicate that the processes of inorganic carbon and nutrient uptake and assimilation are affected by elevated CO₂ due to changes in enzyme activity, which change the energy balance and physiological status of C. officinalis, therefore affecting its competitive interactions with other macroalgae. The ecological implications of the physiological changes in C. officinalis in response to elevated CO₂ are discussed.

Key words: Calcification, carbon dioxide, carbonic anhydrase, coralline algae, nitrate reductase, ocean acidification.

Introduction

Increasing atmospheric CO₂ emissions are changing the chemistry in the surface layer of global oceans. As more CO₂ dissolves into the seawater, changes in the speciation of inorganic carbon occur, resulting in more bicarbonate ions (HCO₃⁻), more protons (H⁺), and fewer carbonate ions (CO₃²⁻). The consequences of these changes are a lower pH and CO₃²⁻ saturation state of the seawater. By the end of this century, the pH of surface oceans is expected to drop by 0.3–0.5 units (Caldeira and Wickett, 2003; Feely et al., 2004; Orr, 2005) due to increasing concentrations of atmospheric CO₂ that could reach up to 970 µatm CO₂ (Houghton et al., 2001). Such changes in seawater chemistry could have severe impacts on calcifying organisms, which rely on inorganic carbon for producing their shells and skeletons, which consist of calcium carbonate (CaCO₃).

Several studies have shown negative responses of corals, macroalgae, and molluscs to elevated seawater CO₂ concentrations (Anthony et al., 2008; Jokiel et al., 2008;
Martin et al., 2008; Martin and Gattuso, 2009; Albright et al., 2010; Diaz-Pulido et al., 2011; Rodolfo-Metalpa et al., 2011; Hofmann et al., 2012b). However, due to the increase in ocean acidification research in the past few decades, it is now clear that calcifying marine organisms show a variety of responses, due to differences in the substrate (HCO$_3^-$ or CO$_3^{2-}$) used for calcification, their ability to control the pH at the location of calcification, the crystalized form of CaCO$_3$ deposited, and the production of protective organic layers that prevent dissolution (Ries, 2009, 2011; Hurd et al., 2011; Jokiel, 2011a,b; Rodolfo-Metalpa et al., 2011; Roleda et al., 2012). Furthermore, studies have shown that physiological processes other than calcification, such as photosynthesis, nutrient assimilation, and growth, are also affected by elevated CO$_2$ concentrations (Magnusson et al., 1996; Mercado, 1999; Gordillo et al., 2001, 2003; Israel and Hophy, 2002; Zou, 2005; Connell and Russell, 2010; Zou et al., 2011; Hofmann et al., 2012b). The physiological and ecological responses of calcifying organisms to elevated CO$_2$ is therefore species-specific, and also depends on local conditions, such as nutrient availability (Ries, 2009; Russell et al., 2009; Fabricius et al., 2011; Price et al., 2011; Hofmann et al., 2012a). It is nevertheless important to understand how all processes, not just calcification, will be affected by elevated CO$_2$, and what implications these changes will have for calcifying organisms.

In calcifying primary producers, photosynthesis is also affected by increasing CO$_2$ levels. However, the responses of these organisms are again variable, because of different mechanisms and efficiencies of obtaining CO$_2$ for photosynthesis. Because the ambient seawater concentration of HCO$_3^-$ is much higher than that of CO$_2$, marine algae have mechanisms called carbon-concentrating mechanisms (CCMs) which transport HCO$_3^-$ across cell membranes using ion transporters, or catalyse the dehydration of HCO$_3^-$ to CO$_2$ via the membrane-associated external carbonic anhydrase (Johnston, 1991; Badger and Price, 1994; Raven, 1997, 2003; Raven et al., 2002). In non-calcifying algae, CCMs have been shown to be down-regulated under elevated CO$_2$ conditions. This down-regulation relieves algae from the high energy demands of producing ion transporter proteins and enzymes (Raven, 2011; Raven et al., 2012). However, in calcifying algae, this enzyme may play an additional role in calcification, and has been shown to increase under elevated CO$_2$ (Isenberg et al., 1963; Hofmann et al., 2012b).

Nutrient assimilation and uptake are further metabolic processes that may be affected by higher CO$_2$ concentrations. Because the speciation of inorganic nitrogen and phosphate is affected by pH, the preference and uptake of inorganic nutrients may be affected, as well as the enzymatic activity involved in nutrient assimilation. Non-calcifying macroalgae have been shown to decrease nitrate uptake under elevated CO$_2$ (García-Sánchez et al., 1994; Magnusson et al., 1996; Andria et al., 1999). Such changes in metabolism are likely to have significant effects on macroalgal nutritional content, which could have implications for grazers and competitive interactions between species. To date, however, there have not been many studies investigating how inorganic carbon and nutrient-related enzymatic activity in calcifying macroalgae will respond to elevated CO$_2$.

Seasonal changes in temperature, nutrient availability, and light are also likely to interact with the effect of CO$_2$ on metabolic processes in algae (Tyrrell et al., 2008; Martin and Gattuso, 2009; Mercado and Gordillo, 2011). As calcification, photosynthesis, nutrient uptake, growth, and other metabolic processes are affected by temperature, light, and nutrient availability, changes in these factors are likely to have a strong influence on the enzymatic response of macroalgae to increasing CO$_2$. Therefore, mesocosm studies such as this one are useful for monitoring CO$_2$ effects over time during natural temperature, nutrient, and light fluctuations.

Both calcifying and non-calcifying algae provide important habitat and shelter for many marine organisms, and erect calcifying algae such as Corallina officinalis contribute to the strength of the intertidal community structure and provide refugia for organisms in environments with high wave action (Dommasnes, 1968; Stewart, 1982; Coull and Wells, 1983; Kelaher, 2002, 2003). Corallina spp. often form extensive macroalgal beds that cover large areas of the intertidal zone and provide substratum, habitat, and refugia for a number of important marine organisms (Coull and Wells, 1983; Hicks, 1977; Akioka et al., 1999; Kelaher, 2002, 2003). The important ecological roles served by this alga could be interrupted under high CO$_2$ conditions, as its skeleton contains high-Mg calcite, the most soluble form of CaCO$_3$ found in calcifying marine macroalgae (Andersson et al., 2008). It is therefore important to understand how its metabolism may be affected in the future. Therefore, a mesocosm study was conducted with macroalgal communities containing the calcifying rhodophyte C. officinalis grown under three different CO$_2$ concentrations. The competitive interactions between C. officinalis and non-calcifying macroalgae as well as the overall macroalgal community response are discussed in a separate paper (Hofmann et al., 2012a).

Here the focus is on inorganic nutrient uptake rates and the enzymatic activity of carbonic anhydrase and nitrate reductase in C. officinalis grown under elevated CO$_2$ conditions.

**Materials and methods**

**Experimental design and seawater chemistry**

The experiment was conducted in 75 litre mesocosms on the German island of Sylt in the North Sea. Experimental conditions including mesocosm set-up, duration, and the inorganic carbon chemistry of the seawater are outlined in Hofmann et al. (2012a). Temperature, salinity, and pH were monitored daily. Seawater samples for inorganic nutrient analysis were taken weekly from the seawater source flowing into all tanks. Nutrient uptake rates were calculated based on a 3h incubation of C. officinalis in 5 litre plexiglass chambers continuously bubbled with mixed gas (386, 665, or 1486 µmol CO$_2$). Rates were calculated after doubling the projected surface area of the algal thalli, which was measured using the imaging analysis software ImageJ (National Institute of Mental Health, Bethesda, MD, USA).
**Results**

Seasonal variability of temperature and inorganic nutrients

The mean seawater temperature in the mesocosm tanks during the experimental period is shown in Fig. 2. Temperature increased linearly with time from the end of March to the beginning of July 2011, and ranged from 6°C to 19°C. The seawater concentrations of nitrate, nitrite, ammonium, phosphate, and silicate are shown in Fig. 3. Nitrate concentrations in the seawater ranged from 6.7 µM to 38.9 µM and were highest in March, at the beginning of the experiment, and declined rapidly to a minumum 40 d after the experiment began. Nitrate levels then began to increase again, but only reached 37% of the initial concentration by the end of the experiment. Silicate concentrations followed a similar pattern, but reached higher than initial levels at the end of the experiment. On the other hand, phosphate concentrations increased during the experiment, and ammonium concentrations ranged from 1.03 µM to 3.06 µM.

Nutrient uptake rates and nitrate reductase activity

Nutrient uptake rates of nitrate, ammonium, and phosphate by *C. officinalis* were measured after 35 d of exposure to the CO2 treatments and are shown in Fig. 4. There was a negative correlation between nitrate uptake and CO2 concentration (Pearson’s correlation coefficient = –0.81, P=0.002). There was no significant treatment effect of CO2 on ammonium or phosphate uptake rates.

Throughout the experimental period, there was a significant effect of time on nitrate reductase activity, as it decreased in all CO2 treatments after 12 weeks. There was also a significant effect of CO2 on nitrate reductase activity (Table 1). Algae grown under ambient CO2 levels had the lowest enzyme activity, while algae grown under 665 µatm CO2 had the highest (Fig. 5A). The relationship between nitrate reductase activity and nitrate uptake rate differed between the CO2 treatments (Fig. 6). The algae grown under elevated CO2 had higher nitrate reductase activity, but lower nitrate uptake rates compared with algae grown in the ambient CO2 treatment.

Carbonic anhydrase activity

All carbonic anhydrase activity (total, internal, and external) was significantly affected by time. External carbonic anhydrase activity was affected by CO2, and internal and external carbonic anhydrase activity was affected by an interaction between time and CO2 (Table 1). Internal carbonic anhydrase showed no observable pattern over time, except for two peaks.
in the 1486 µatm CO₂ treatment after 4 and 8 weeks, and a large drop after 12 weeks. On the other hand, external carbonic anhydrase increased equally in all treatments during the first half of the experiment until week 7 when all treatments levelled off, but the enzyme activity was highest in the 1486 µatm CO₂ treatment and subsequently decreased with decreasing CO₂ level (Fig. 5B, C).

**CaCO₃ content**

Inorganic carbon content of the *C. officinalis* skeleton peaked in all treatments after 3 weeks, and afterwards the CO₂ treatment effect became apparent, as the skeletal inorganic carbon content decreased with increasing CO₂ concentration (Fig. 5D). By the end of the experiment, there was a negative linear relationship between skeletal inorganic content (% DW of CaCO₃) and external carbonic anhydrase activity which was not apparent after shot-term exposure (36 d) to elevated CO₂ (Fig. 7A, B).

**Discussion**

The present results suggest that elevated CO₂ will significantly affect enzyme activity and subsequently many metabolic processes in *C. officinalis*, including photosynthesis, calcification, and inorganic nutrient uptake and assimilation. The enzyme external carbonic anhydrase is important in the CCM of many macroalgae. Although its activity has been shown to decrease in non-calcifying macroalgae in response to elevated CO₂ (Björk *et al.*, 1993; García-Sánchez *et al.*, 1994; Haglund and Pedersén, 2009), an increase in external carbonic anhydrase activity with increasing CO₂ concentration was observed. In non-calcifying macroalgae, there is evidence that less enzyme is produced because more CO₂ is available for photosynthesis, so less HCO₃⁻ must be converted to CO₂ (Giordano *et al.*, 2005a, and references therein; Matsuda *et al.*, 2011). However, in the case of calcifying macroalgae, it is likely that external carbonic anhydrase plays a role in metabolic processes other than photosynthesis, particularly calcification. In corals, carbonic anhydrase has been reported to be an important enzyme in the calcification process (Kingsley and Watabe, 1987; Nimer *et al.*, 1994; Al-Horani *et al.*, 2003; Rahman *et al.*, 2008; Tambutté, 2007). Hofmann *et al.* (2012a) showed that calcification rates in *C. officinalis* had a parabolic relationship to CO₂ concentration, and Hofmann *et al.* (2012b) showed that external carbonic anhydrase showed an increasing trend with elevated CO₂ in the same species. As photosynthesis was not stimulated by CO₂ in this species, despite an increase in
CO₂ affects *C. officinalis* enzyme activity

It is hypothesized that external carbonic anhydrase activity is related to calcification, and that its activity is up-regulated under elevated CO₂. In this way, the algae may regulate the calcification mechanism despite changes in seawater inorganic carbon chemistry that are unfavourable for CaCO₃ deposition. This hypothesis is supported by the relationship observed between external carbonic anhydrase activity and the skeletal inorganic carbon content of *C. officinalis*, which was only revealed after long-term exposure to elevated CO₂. Such a response of the algae could be to compensate for higher dissolution rates under elevated CO₂ conditions (Ries, 2011; Rodolfo-Metalpa et al., 2011). If external carbonic anhydrase does indeed play a role in calcification, higher dissolution rates would explain why an increase in skeletal inorganic carbon was not seen despite an increase in external carbonic anhydrase activity under elevated CO₂.

The overall decrease in nitrate reductase activity in *C. officinalis* grown at all CO₂ concentrations during the first 6 weeks was most probably due to a decline in the seawater nitrate concentration, as the enzyme has been shown to be dependent on external nitrate availability (Solomonson and Barber, 1990; Gordillo et al., 2006). Algae generally prefer ammonium over nitrate as their nitrogen source, as it is less energy costly to assimilate (Losada and Guerro, 1979; Syrett, 1981). The ammonium concentrations were sufficient to supply the algae with an alternative source of nitrogen when the seawater nitrate concentrations, and subsequently nitrate reductase activity, decreased.

The decrease in nitrate uptake rates by *C. officinalis* under elevated CO₂ conditions is consistent with other results found for non-calcifying macroalgae and seagrass (García-Sánchez et al., 1994; Magnusson et al., 1996; Andria et al., 1999; Alexandre et al., 2012) as well as the observed increase in nitrate reductase activity (Mercado et al., 1999; Gordillo et al., 2001; Alexandre et al., 2012). Mercado et al. (1999) reported that the reduction and assimilation of nitrate in *Porphyra leucosticta* grown under elevated CO₂ was uncoupled, which also seems to be the case in *C. officinalis*. Changes in the intracellular ATP:NADP+/NADPH ratio could affect

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**Table 1.** Results from a MANOVA test on enzyme activity and CaCO₃ content (Cinorg) of *C. officinalis* with time as a within-subject factor and CO₂ as a between-subject factor. *F*-ratios are given with degrees of freedom in parentheses, followed by the *P*-values significant at the 95% confidence level.

<table>
<thead>
<tr>
<th>Response variable</th>
<th>Time (within-subject factor)</th>
<th>CO₂ (between-subject factor)</th>
<th>Time×CO₂ (interaction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tCAA</td>
<td>*(9, 81)=15.5, P=2.1E-14</td>
<td>*(2, 9)=36.2, P=5.0E-5</td>
<td>–</td>
</tr>
<tr>
<td>eCAA</td>
<td>*(11, 99)=45.6, P=7.8E-34</td>
<td>*(22, 99)=3.4, P=1.6E-5</td>
<td>F(20, 90)=2.4, P=0.003</td>
</tr>
<tr>
<td>iCAA</td>
<td>*(10, 90)=15.5, P=1.0E-15</td>
<td>*(22, 99)=1.0, P=0.006</td>
<td>F(2, 9)=12.1, P=0.003</td>
</tr>
<tr>
<td>NRA</td>
<td>*(11, 99)=9.4, P=2.5E-11</td>
<td>*(2, 9)=5.0, P=0.034</td>
<td>–</td>
</tr>
<tr>
<td>Cinorg</td>
<td>*(11, 99)=21.4, P=1.5E-21</td>
<td>*(22, 99)=2.1, P=0.006</td>
<td>–</td>
</tr>
</tbody>
</table>

 tCAA, total carbonic anhydrase activity; eCAA, external carbonic anhydrase activity; iCAA, internal carbonic anhydrase activity; NRA, nitrate reductase activity.
nitrate reductase activity, due to the requirement for NADPH as a reducing agent to convert nitrate to nitrite (Corzo and Niell, 1991). Chlamydomonas sp. cells grown under normal CO₂ conditions require higher ATP:NADPH ratios for CO₂ assimilation than high CO₂-grown cells (Spalding et al., 1984). Therefore, if algae grown under elevated CO₂ have a lower ATP:NADPH requirement, the excess NADPH could stimulate nitrate reductase activity. However, this may only be the case when CCMs are down-regulated. In high CO₂-grown C. officinalis, the protein content decreases, indicating a likely decrease in Rubisco concentration. This reduction in Rubisco content could be interpreted as a partial down-regulation of the CCM in C. officinalis, despite the increase in external carbonic anhydrase activity. However, another possible reason for stimulation of nitrate reductase under elevated CO₂ is a change in the plastoquinone pool. Giordano et al. (2005b) reported that nitrate reductase activity is controlled by the redox state of the plastoquinone pool in Chlamydomonas reinhardtii, in that nitrate reductase activity is stimulated by a reduced plastoquinone pool. A reduced plastoquinone pool generally occurs under high light conditions, when the electron transport chain is saturated (Behrenfeld et al., 1998). The lower protein content in C. officinalis grown under elevated

Fig. 5. Time series of mean (±SE, n=4) (A) nitrate reductase activity, (B) external carbonic anhydrase activity, (C) internal carbonic anhydrase activity, and (D) percentage inorganic carbon of C. officinalis exposed to three carbon dioxide concentrations. Circles, 385; squares, 665; and triangles, 1486 µatm CO₂.

Fig. 6. Mean nitrate reductase activity (±SE, n=4) as a function of mean nitrate uptake rates in C. officinalis exposed to the three CO₂ levels. Circles, 385; squares, 665; and triangles, 1486 µatm CO₂.
CO₂ (Hofmann et al., 2012a) suggests that Rubisco content may be lower in algae grown under high CO₂ conditions. When CO₂ concentrations are saturating for photosynthesis, activation of Rubisco can be rate limiting to photosynthesis rather than electron flow (Dietz and Herber, 1984). The combination of high light conditions during summer and lower Rubisco content under elevated CO₂ could have resulted in a more reduced plastoquinone pool in C. officinalis grown under elevated CO₂, causing the stimulation of nitrate reductase activity.

The absolute values and seasonal pattern of seawater temperature in the mesocosm tanks and ambient seawater nutrient concentrations were consistent with previously recorded seasonal trends in the Wadden Sea (van Beusekom et al., 2001, 2010). Therefore, the changes in both enzyme activities during the experimental period indicate that there was an effect of seasonally changing temperature and nutrient conditions on C. officinalis metabolism. However, the enzymes responded differently to seasonal fluctuations, as nitrate reductase increased and external carbonic anhydrase decreased during the first 6 weeks of the experiment. The increase in external carbonic anhydrase activity in all treatments during the first 6 weeks was most probably a response to increasing seawater temperature, as enzymes have optimum temperatures for maximum activity, and C. officinalis growth is optimal at temperatures between 12 °C and 18 °C (Colthart and Johansen, 1973), which were reached after the first half of the experiment. The stimulation of carbonic anhydrase by elevated temperature has been previously reported for Chlorella vulgaris (Shiraiwa and Miyachi, 1985). This temperature effect could have masked the CO₂ effect during the first 6 weeks of the experiment, as there was no difference in external carbonic anhydrase activity between the CO₂ treatments until after 6 weeks. Therefore, the enzymatic activity, reliant metabolic mechanisms, and cellular products of the calcifying red alga C. officinalis will be affected by CO₂, but will also depend on seasonal effects such as nutrient availability and temperature.

The present results indicate that the response of C. officinalis to elevated CO₂ is complex, and involves many metabolic processes other than just calcification and photosynthesis. The observed changes in enzyme activity, combined with changes in photosynthesis, calcification, and cell nutritional content reported by Hofmann et al. (2012a), will alter the competitive status of C. officinalis under future oceanic CO₂ conditions, which could have implications for macroalgal communities and their grazers. However, it is still unclear if calcifying coralline algae, such as C. officinalis, will be able to adapt to increasing CO₂ concentrations that will allow them to maintain their current competitive status within macroalgal communities. Their ability to adapt will most probably depend on other abiotic factors and seasonal patterns. Therefore, it will be important to conduct future experiments on different life history stages of this alga, as well as to follow the responses of multiple generations to elevated CO₂ under conditions which simulate seasonal changes.

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