

Carbon and nitrogen fluxes in the marine coccolithophore *Emiliana huxleyi* grown under different nitrate concentrations

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ABSTRACT

Information on interaction of C and N at the cellular level is lacking for ecologically relevant phytoplankton species. We examined the effects of NO₃ availability on C and N fluxes in the widely distributed marine coccolithophore *Emiliana huxleyi*. Cells were cultured at replete (~280 μM) and ambient (~10 μM) NO₃, the latter representing a typical surface water nitrate concentration of the North Atlantic Ocean during spring. While growth rates and C to N ratios were not altered by the NO₃ availability, organic C and N as well as inorganic C quotas were reduced under ambient NO₃. Growth at ambient NO₃ caused a higher proportion of fixed C to be allocated to lipids relative to carbohydrates and especially to proteins. Ambient NO₃-grown cells showed lower V_{max} of nitrate reductase (NR) and nitrite reductase (NiR) (ambient/replete: V_{max}^{NR} = 0.64/1.09 fmol min⁻¹ cell⁻¹; V_{max}^{NiR} = 0.3/0.56 fmol min⁻¹ cell⁻¹), whereas they had higher V_{max} of glutamine synthetase (GS) and glutamate synthase (GOGAT) (ambient/replete: V_{max}^{GS} = 0.57/0.38 fmol min⁻¹ cell⁻¹; V_{max}^{GOG} = 3.91/2.87 fmol min⁻¹ cell⁻¹). In these cells, photosynthetic O₂ evolution and HCO₃⁻ uptake rates were lower as compared to replete NO₃-grown cells (ambient/replete: V_{max}^{O₂} = 6.5/12.9 fmol min⁻¹ cell⁻¹; V_{max}^{HCO₃⁻} = 2.8/8.1 fmol min⁻¹ cell⁻¹). The CO₂ uptake and the maximum light use efficiency of photosynthesis (α) were unaffected by the concentration of NO₃. The affinities of NR for NO₃, of NiR for NO₂, of GS for Glu, and of the inorganic carbon uptake system for HCO₃⁻ were higher under ambient NO₃ (ambient/replete: K_m^{NR} = 0.074/0.099 mM; K_m^{NiR} = 1.69/3.14 mM; K_m^{GS} = 1.62/3.81 mM; K_m^{HCO₃⁻} = 195/524 μM). Our data suggest that a concerted regulation of the intracellular CO₂ and NO₃ concentrations is required to maintain balanced C and N metabolic fluxes resulting in a constant C to N ratio.

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1. Introduction

Assimilation of C and N consume the largest part of ATP and reductants generated in the cell (Huppe and Turpin, 1994). Although competing for energy, the acquisition and metabolism of C and N must be tightly coupled. This is due to the fact that the boundaries of the C to N ratio are defined by the stoichiometry of key components of the cell machinery, such as amino acids, proteins, nucleic acids and chlorophylls (Turpin, 1991 and references therein). The relative size of the different pools, within the above mentioned boundaries, is determined by the N availability relative to C in the environment (Giordano et al., 2001; Palmucci and Giordano, submitted for publication).

Much information on NO₃ assimilation is available for model microalgae such as *Chlamydomonas reinhardtii* (Fernandez and

Galvan, 2008 and references therein), but very little is known for ecologically relevant phytoplankton species. In this study, we focused on the widely distributed coccolithophore *Emiliana huxleyi* (Winter et al., 1994). This organism provides an important contribution to the marine primary production and it is considered to be one of the major producers of calcite in the ocean (Baumann et al., 2004). Very limited data has been published on the NO₃ acquisition by *E. huxleyi* (Page et al., 1999; Riegman et al. 2000). Some data are available for *E. huxleyi* nitrate reductase (NR), which shows some unique properties compared to the NR proteins of other microalgae (Iwamoto and Shiraiwa, 2003). Native *E. huxleyi* NR has an overall mass of 514 kD and is composed of six 85 kD homologous subunits (Iwamoto and Shiraiwa, 2003). The K_m for NADH and NO₃ of purified NR were 40 μM and 104 μM, respectively (Iwamoto and Shiraiwa, 2003). No information is available for *E. huxleyi* nitrite reductase (NiR), the enzyme responsible for the subsequent reduction of NO₂ to NH₄⁺. The NH₄⁺ generated thanks to the catalysis by NiR is incorporated into amino acids via the glutamine synthetase/ glutamate synthase (GS/GOGAT) cycle. Two different GS isoforms of the enzyme, one located in the

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cytosol (GS₁), the other located in the chloroplast (GS₂), have been partially characterized in *E. huxleyi* by Maurin and Le Gal (1997a). Both isoforms are homo-hexamers with molecular masses of 402 kD for GS₁ and 501 kD for GS₂, whereas the molecular masses of the subunits of GS₁ and GS₂ were estimated to be 61 and 70 kD, respectively (Maurin and Le Gal, 1997a). The same authors reported that the K_m for hydroxylamine (NH₂OH) was approximately 3 mM for both GS isoforms, but GS₂ had higher affinity for Gln than GS₁. Maurin and Le Gal (1997b) also showed that *E. huxleyi* total GS activity was stimulated by decreasing NO₃ availability and the affinity of GS for NH₄⁺ was higher in N limited cells. In contrast to GS, no data is available in the literature for *E. huxleyi* GOGAT. The synthesis of amino acids via the GS/GOGAT system typically requires C skeletons from the TCA cycle (Elfiri and Turpin, 1986; Weger and Turpin, 1989).

Almost the entire C contained in macromolecular compounds such as proteins and lipids is fixed by Rubisco. Since Rubisco is characterized by a low affinity for CO₂, microalgae cells have to invest a substantial amount of energy to enhance CO₂ concentration at the carboxylation site of Rubisco and avoid inorganic carbon (Ci) limitation (Badger et al., 1998). Therefore, cells have developed biophysical and, possibly, biochemical carbon concentrating mechanisms (CCMs) that operate to increase the availability of CO₂ for Rubisco (Giordano et al., 2005a and references therein). While it has been shown that the photosynthetic C acquisition of *E. huxleyi* was regulated in response to light and CO₂ (Rost et al., 2003; Rost et al., 2006; Trimbom et al., 2007), the effect of N availability on the CCM has not been studied in this species. The CCMs have been suggested to improve N-use efficiency in microalgae, mainly by increasing the achieved rate of CO₂ fixation per unit N in Rubisco (Raven, 1997; Beardall et al., 1998), thereby controlling the cellular elemental ratios, specifically the C to N ratio (Beardall and Giordano, 2002).

In this study, we intend to gain a better understanding of the regulation of intracellular processes that define the C to N ratio in a common phytoplankton cell. With this aim in mind, we investigated the regulation of cellular C and N fluxes and the relative composition of macromolecular pools in response to NO₃ availability in *E. huxleyi*.

2. Materials and methods

2.1. Culture conditions

The coccolith-bearing strain B 92/11 (J. C. Green 1990, Plymouth Marine Laboratory) of *E. huxleyi* was grown in semi continuous cultures in 10 L polycarbonate flasks. Experiments were carried out under a 16:8 h light:dark (LD) cycle at a constant temperature of 15 °C. The applied mean photon flux density was 240 μmol photons m⁻² s⁻¹. The culture flasks were aerated with air containing a CO₂ partial pressure (pCO₂) of 37.5 Pa and placed on a shaker, to keep the cells in suspension. The growth medium was prepared from sterile-filtered (0.2 μm pore-size cellulose-acetate filters, Sartorius) natural seawater. Nutrient additions, with the exception of iron and NO₃, were made according to the f/2 recipe (Guillard and Ryther, 1962). The iron concentration in the culture medium was 8 nM and was sufficient to cover the iron need of the relative low cell densities in our experiment, as determined in preliminary experiments. Cells were grown in a semi-continuous mode which allowed for relatively constant growth conditions (LaRoche et al., 2010). Over the course of the experiment, cell densities were kept between 3 × 10⁴ cells mL⁻¹ (after dilution) and 3 × 10⁵ cells mL⁻¹ (before dilution). The initial NO₃ concentrations in the growth media were ca. 280 μM in the replete and ca. 10 μM in the ambient NO₃ treatment (Fig. 1a). Generally, cells were harvested at a density of 3 × 10⁵ cells mL⁻¹. Cells grown at the ambient NO₃ concentration were harvested before the onset of growth limitation (Fig. 1b). Growth rates and cell volume were calculated from daily cell counts by means of a cell counter (COULTER

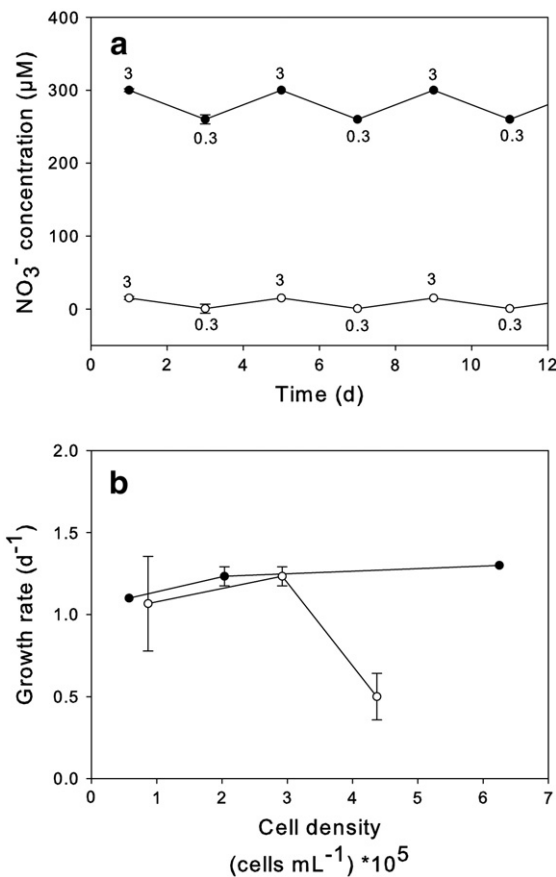


Fig. 1. The variability of NO₃ concentrations over the course of the experiment (cell densities are shown with numbers in units of 10⁵ cells mL⁻¹) (1a) and the relationship between growth rates and cell densities in cells grown at replete (●) and ambient (○) NO₃ (1b). Incremental growth rates were calculated on the basis of daily cell counts. Values represent an average of triplicates (± SD).

MULTISIZER 3, Beckmann). Before measurements, cells were acclimated to the experimental conditions for at least 14 d.

2.2. Elemental composition and coccolith morphology

Samples for total particulate C (TPC), particulate organic C (POC) and N (PON) were filtered on precombusted (500 °C, 12 h) filters (nominal pore size 0.6 μm GFF filters, Whatman) and stored in precombusted (500 °C, 12 h) petri-dishes at -20 °C. Filters for POC were treated before analysis with 200 μl HCl (0.1 M) to remove all inorganic C. TPC, POC and PON samples were measured on an elemental analyzer mass spectrometer (ANCA-SL 2020, Sercon). Values for particulate inorganic carbon (PIC) were calculated as the difference between TPC and POC. Regarding the morphology of coccoliths, samples for scanning electron microscope analysis were filtered on polycarbonate filters (0.2 μm pore size, Whatman), dehydrated in a drying cabinet at 60 °C for 24 hours, then sputter-coated with gold-palladium. Imaging was performed with a digital scanning field-emission electron microscope (XL-30, Philips). Four categories were used to describe the morphology of *E. huxleyi* coccoliths: 'normal', 'malformed', 'incomplete', and 'incomplete and malformed'. An average of approx. 350 coccoliths was analyzed per sample.

2.3. Macromolecular pools

The relative amounts of macromolecular pools were determined via Fourier Transform Infrared (FTIR) spectroscopy analysis. Cells for FTIR spectroscopy analyses were harvested by centrifugation at

1,500×g for 15 minutes and washed twice with an isoosmotic solution of ammonium formate, to minimize the carry-over of IR absorbing medium components. Cells were resuspended in ammonium to obtain the concentration that was preliminary determined to afford the best signal to noise ratio. Aliquotes of 50 µL of these suspensions were deposited on silica windows (Crystran Ltd., Poole, UK) and desiccated in an oven at 60 °C for at least 3 hours. Silica windows on which 50 µL of ammonium formate solution were deposited were treated as the samples and used as blanks (Domenighini and Giordano, 2009).

FTIR spectra were acquired with a Tensor 27 FTIR spectrometer (Bruker Optics, Ettlingen, Germany) as described in Domenighini and Giordano (2009). All spectra were baseline corrected prior to any analysis by the application of the Rubberband correction function of the OPUS 6.5 software (Bruker Optics, Ettlingen, Germany); they were then normalized to the amide I band (~1650 cm⁻¹). Bands were assigned to the macromolecular pools according to Giordano et al. (2001). The sum of the integrals of the absorption bands at ~1160 cm⁻¹, ~1080 cm⁻¹ and ~1030 cm⁻¹ was used as a proxy for carbohydrates. The amide I peak (1650 cm⁻¹) was used as an indicator of protein relative abundance. The ~1740 cm⁻¹ feature was used for lipids. Relative ratios of protein, carbohydrates and lipids were calculated from the bands' integrals, using the OPUS 6.5 software (Bruker Optik GmbH, Ettlingen, Germany). The calculation of the band integrals was performed after deconvolution of the spectrum from 1800 cm⁻¹ to 1000 cm⁻¹ using the Peak fit function of OPUS 6.5; to minimize subjective assessments, the main peaks on which deconvolution was based were identified by the application to each spectrum of a second derivative, with 9 smoothing points.

2.4. Enzymes of nitrate assimilation

NR activity in phytoplankton often exhibit diurnal variations when grown in a LD cycle. To allow a direct comparison of enzyme activities between cells grown under replete and ambient NO₃ concentrations, the samples were taken at the same time of day for both NO₃ treatments. The cells were harvested during the fourth hour of the photoperiod. Cells were concentrated by centrifugation at 2,772×g for 6 min at 4 °C (Megafuge 1.0 R, Heraeus), frozen in liquid N₂ and stored at -80 °C. The cells were gently disrupted at 4 °C, using a hand operated glass homogenizer (Wheatman). The extracts were then centrifuged at 16,060×g for 15 min at 4 °C (Biofuge fresco, Heraeus), in order to spin down the calcite. The supernatant was centrifuged again at 61,740 g for 20 min at 4 °C (OPTIMA™ LE-80 K Ultracentrifuge, Beckmann) to get rid most of the cell membrane fractions. The resulting supernatant was used to study enzyme kinetics and measure total protein amount. The protein amount in extracts was measured according to the method of Bradford (1976), using BSA as standard. All solutions were made in Milli-Q H₂O (Milli-Q academic A10, Millipore) and the chemicals were purchased by Sigma-Aldrich (St. Louis, MO, USA).

2.4.1. NR activity

NR activity was determined by NO₃ reduction to NO₂ and subsequent colorimetric measurement of the NO₂ produced according to the method described by Giordano et al. (2005b). The extraction buffer for NR (buffer A) contained 50 mM HEPES (pH 7.5), 1 mM EDTA, 1 mM dithiothreitol, 0.1% Triton X-100 (v/v), 0.3% polyvinylpyrrolidone (w/v) and 10 mM MgSO₄. The amount of NO₂ was measured according to the method of Snell and Snell (1949) in a microplate reader (SPECTRAFLUOR, Tecan) at 535 nm. Controls included the same reaction mixture, but extraction buffer was used instead of extract. The amount of NO₂ in the tubes was quantified according to a NO₂ standard curve from 0 to 40 µM. Nitrate concentrations from 0.005 to 20 mM were used for the determination of NR kinetic parameters.

2.4.2. NiR activity

Activities of NiR were determined using an assay described by Wray and Filner (1970), which is based on the colorimetric measurement of the NO₂ left in the reaction mixture. Buffer A was used for NiR extraction and the reaction was run in open tubes. The assay mixture contained in a total volume of 500 µL: 100 µL of 150 mM phosphate buffer (pH 7.5), 20 µL Milli-Q H₂O, 250 µL of 32 mM NaNO₂, 5 µL of a 100 mM methyl viologen solution, 50 µL of extract and 75 µL of fresh Na₂S₂O₄ (25 mg mL⁻¹ Na₂S₂O₄ in 0.29 M NaHCO₃) solution. This mixture was incubated at 30 °C for 15 min. The reaction was initiated by adding the sodium dithionite solution. The reaction was stopped by vigorous shaking until the dithionite was completely oxidized and the solution turned from dark blue to colourless. Controls included the same reaction mixture, but extraction buffer was used instead of extract. The amount of NO₂ was measured in a microplate reader (SPECTRAFLUOR, Tecan) at 535 nm according to the method of Snell and Snell (1949) with a standard curve from 0 to 40 µM NO₂. Nitrite concentrations from 0.25 to 16 mM were used in the assay, in order to determine the NiR kinetic parameters.

2.4.3. GS activity

GS activity was determined from the formation of L-Glu γ-monohydroxamate as described by O'Neal and Joy (1973), and Oaks et al (1980). The extraction buffer for GS (buffer B) contained 50 mM HEPES (pH 7.5), 1 mM EDTA, 2 mM dithiothreitol, 0.1% Triton X-100 (v/v), 0.3% polyvinylpyrrolidone (w/v) and 10 mM MgSO₄. The extracts were desalted by applying them on a Sephadex column (PD-10 DESALTING COLUMN, GE Healthcare, Uppsala, Sweden). The extracts were eluted using 50 mM HEPES (pH 7.5). An assay mixture containing 160 mM HEPES (pH 7.5), 4.8 mM hydroxylamine (pH 7.5), 3.2 mM MgSO₄ and 0.16 mM EDTA was prepared. The reaction was conducted in a 96-well plate in a final volume of 200 µL. To a 76.4 µL aliquot of the assay mixture, we added 25.6 µL of 6.25 mM ATP (pH 7.5) and 76.8 µL extract. The reactants were incubated for 5 min at 30 °C. At last, 21.2 µL of 0.6 M Glu were added, the microplate was incubated for 20 min at 30 °C. The reaction was terminated by adding 40 µL of a FeCl₃ solution [2.5% FeCl₃ (w/v), 5% TCA (w/v), 1.5 N HCl]. The reactants were centrifuged at 16,060×g for 2 min. Controls were run, in which 50 mM HEPES (pH 7.5) was used instead of extract. A second control was run, in which the reaction was stopped by adding the FeCl₃ solution immediately after the Glu addition. The amount of L-Glu γ-monohydroxamate was measured in a microplate reader at 535 nm with a standard curve from 0 to 25 µM γ-L-Glu monohydroxamate. Glu concentrations from 0.5 to 63.6 mM and hydroxylamine (NH₂OH) concentrations from 0.02 to 4.8 mM were used to derive GS kinetic parameters.

2.4.4. GOGAT activity

GOGAT activity was determined by the reduction in the absorbance of NADH similar to the methods of Singh and Srivastava (1986) and Lin and Kao (1996). Buffer A was used for GOGAT extraction. The assay mixture contained 125 mM HEPES (pH 7.5), 5 mM EDTA, 20 mM KCl and 875 µM NADH. The reaction was conducted in a 96-well plate in a final volume of 250 µL. To a 50 µL aliquot of the assay mixture, we added 100 µL extract, 50 µL of 20 mM Gln and 50 µL of 5 mM α-ketoglutarate. Controls included the same reaction mixture, in which the extract was substituted with extraction buffer. The reduction in NADH absorbance at 340 nm was measured in a microplate reader (SPECTRAFLUOR, Tecan) at 30 °C for 2 min, immediately after the addition of α-ketoglutarate.

2.5. Photosynthesis and Ci acquisition

Ci fluxes during steady-state photosynthesis were investigated by means of a sector-field multicollector mass spectrometer (ISOPRIME, GV Instruments, Manchester, UK). Net photosynthesis was measured by monitoring the O₂ concentration over consecutive LD intervals

with increasing C_i concentrations (0 to ~5 mM). Light and dark intervals during the assay lasted 6 min. Simultaneous measurements of the CO_2 concentration enabled us to determine the CO_2 uptake and HCO_3^- uptake kinetics according to equations by Badger et al. (1994), using a photosynthetic quotient (PQ) of 1.4 (Williams and Robertson, 1991). To provide conditions similar to the acclimation, all measurements were performed at 15 °C in buffered f/2 medium (50 mM HEPES, pH 8.0) with NO_3^- concentrations of 300 and 10 μM , respectively. Dextran-bound sulfonamide (DBS), a membrane-impermeable inhibitor of carbonic anhydrase, was added to the cuvette to a final concentration of 100 μM . Chl *a* concentration ranged between 0.5 and 1 mg mL⁻¹. The incident photon flux density was 300 μmol photons m⁻² s⁻¹. For further details on the method and calculation, we refer to Badger et al. (1994) and Rost et al. (2007). The kinetic parameters V_{max} and $K_{1/2}$ were obtained by fitting the data with a Michaelis-Menten equation.

Furthermore, net photosynthesis was measured under various light intensities (0 to 800 μmol photons m⁻² s⁻¹). While the same buffer (HEPES 50 mM, pH 8.0) and respective NO_3^- concentrations (300 versus 10 μM) were used as in the C_i flux assay measurements, the C_i concentration were kept at ~2 mM. This way rates of photosynthesis, both expressed in terms of O_2 evolution and carbon fixation, could be measured as a function of PFD. The light-saturated photosynthetic rate as a function of irradiance (*E*) was calculated from the equation

$$V = V_{max} \left(1 - \exp \left(- \frac{\alpha}{V_{max}} (E - E_k) \right) \right),$$

where *V* is the rate of photosynthesis, V_{max} is the maximal rate of photosynthesis and E_k is the light compensation point. The unit of the maximum light use efficiency of photosynthesis (α) is μmol O_2 (mg Chl *a*)⁻¹ h⁻¹ (μmol photon m⁻² s⁻¹)⁻¹.

2.6. Statistical analysis

All data were statistically analyzed using the t-test (one-tailed) with a confidence level of 95% (see Table S1 in the Supplementary Material).

3. Results

3.1. Growth, elemental composition and coccolith morphology

The growth rates were quite similar (1.1 to 1.2 d⁻¹) for the two NO_3^- treatments. The cell volume, however, was one-fourth lower in cells at ambient NO_3^- (Table 1; Table S1). At ambient NO_3^- , cells accumulated less organic C and N and the cellular POC content was ca. one-third lower (Table 1; Table S1). Similarly, cells grown at ambient NO_3^- contained one-third less PON than their high NO_3^- counterparts (Table 1; Table S1). Despite changes in POC and PON content, the C to N ratio remained constant and was about 8.3 to 8.5 in both NO_3^- treatments (Table 1; Table S1). The cellular PIC content was approximately one-fourth lower at ambient NO_3^- (Table 1; Table S1). The PIC to POC ratio was 0.6 to 0.7 (as can be calculated from the POC and PIC values in Table 1) and remained constant irrespective of the NO_3^- levels in the experiment. Cells produced mostly incomplete coccoliths when grown at ambient NO_3^- (Figs. 2 and 3). In contrast,

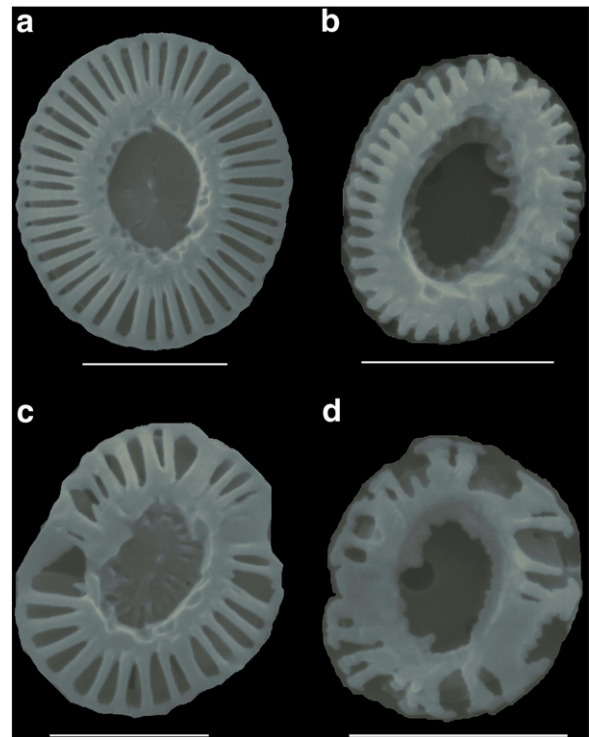


Fig. 2. Scanning electron microscopy images of coccoliths of *E. huxleyi*. All scalebars 2 μm . All specimens in distal view. (a) normal coccolith. (b) incomplete coccolith. (c) malformed coccolith. (d) incomplete and malformed coccolith.

almost all coccoliths produced by cells at replete NO_3^- were normal (Figs. 2 and 3).

3.2. Macromolecular pools

The allocation of C into the macromolecular compounds was affected by the NO_3^- condition in the culture medium. Cells in the ambient NO_3^- treatment were characterized by ca. one-third lower protein content (Table 1; Table S1). The abundance of proteins relative to lipids, as determined by FTIR spectroscopy, was lower at ambient NO_3^- ; the opposite was true for the proteins to carbohydrates and lipids to carbohydrates (Table 2; Table S1). The comparison of the FTIR data with the absolute protein determinations allows to conclude that at ambient NO_3^- , the lower protein content is accompanied by an even more obvious reduction of the carbohydrate pool, whereas the lipid pool appears to be affected by the growth treatment. Although, the relative nature of FTIR measurements performed for this work makes it impossible to determine the extent of these variations.

3.3. Enzymes of nitrate assimilation

N availability was found to affect the kinetics of both NR and NiR (Figs. S1 and 2). NR V_{max} was 1.7-fold lower in cells at ambient NO_3^- compared to cells grown at replete NO_3^- , when it was expressed on a cell basis (Table 3; Table S1). When expressed on a protein basis, cell volume, C or N, NR V_{max} was basically unaffected by the NO_3^- concentration in the medium. The affinity of NR for NO_3^- was

Table 1
Specific growth rate (μ), cell volume (CV), particulate organic carbon (POC), particulate inorganic carbon (PIC), particulate organic nitrogen (PON), protein content and C to N ratio in cells grown at replete and ambient NO_3^- . The values represent the means of triplicate incubations (\pm SD).

NO_3^- (μM)	μ (d ⁻¹)	CV (μm^3)	POC (pg cell ⁻¹)	PIC (pg cell ⁻¹)	PON (pg cell ⁻¹)	Protein (pg cell ⁻¹)	C to N ratio (mol mol ⁻¹)
Replete	1.2 \pm 0.1	394 \pm 46	13.9 \pm 2.4	8.7 \pm 0.9	1.9 \pm 0.2	1.7 \pm 0.1	8.5 \pm 0.5
Ambient	1.1 \pm 0.2	272 \pm 37	9.3 \pm 0.8	6.6 \pm 0.9	1.3 \pm 0.1	1.2 \pm 0.1	8.3 \pm 0.9

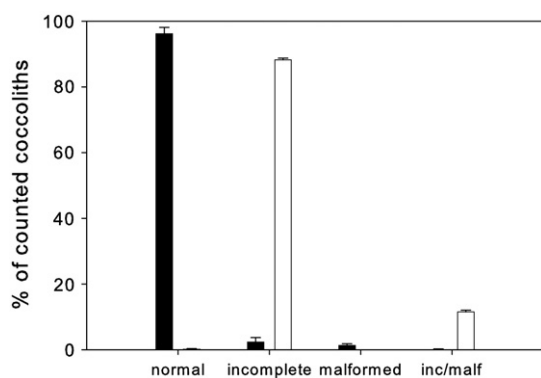


Fig. 3. Percentage of normal, malformed, incomplete, and incomplete and malformed (inc/malf) coccoliths in cells grown at replete (■) and ambient (□) NO_3^- . Values represent an average of duplicates (\pm SD).

significantly higher in cells at ambient NO_3^- (Table 3; Table S1). Regardless of the basis on which it was expressed, NiR V_{max} was lower at ambient NO_3^- (Table 3; Table S1). The affinity of NiR for NO_2^- was substantially higher at ambient NO_3^- (Table 3; Table S1).

The different NO_3^- concentrations also affected GS kinetics (Fig. S3). At ambient NO_3^- , GS V_{max} was higher and this relationship was independent of the type of normalization (Table 3; Table S1). Regarding total GS affinities, the affinity for Glu was two-fold higher in cells grown at ambient NO_3^- than in their counterparts (Table 3; Table S1). The affinity of total GS for NH_2OH was similar in cells of both NO_3^- treatments (Table 3; Table S1). Similar to GS V_{max} , GOGAT V_{max} was higher in cells grown at the ambient NO_3^- regime, irrespective of the parameter on which the enzyme activity was expressed (Table 3; Table S1).

3.4. Photosynthesis and Ci acquisition

The maximum rate of net photosynthesis expressed on a per cell basis was about two-fold lower in cells at ambient NO_3^- (Table 4; Table S1; Fig. S4). When net photosynthesis was expressed on a mg Chl *a* basis, no difference was observed between cells of the high and low NO_3^- treatment. This is a consequence of the fact that the amount of Chl *a* was about two-fold lower in cells at ambient NO_3^- (data not shown). However, at ambient NO_3^- , the affinities of photosynthesis for CO_2 and DIC were higher (Table 4; Table S1; Fig. S4). The light curve of net photosynthesis revealed that maximum light use efficiency of photosynthesis (α) was similar between the two NO_3^- treatments (Table 4; Table S1).

Maximum gross CO_2 uptake (uptake of CO_2 into the cell) and net CO_2 uptake (gross CO_2 uptake minus CO_2 efflux) rates (V_{max}) per cell were similar in high and low NO_3^- -grown cells (Table 4; Table S1; Fig. S5A and SB). The affinities of net and gross CO_2 uptake for CO_2 were not affected by the different NO_3^- conditions (Table 4; Table S1). The effects of N availability were stronger on the uptake of HCO_3^- (Fig. S6). The rate of HCO_3^- uptake was ca. four-fold lower in cells at ambient NO_3^- (Table 4; Table S1). Whereas the rate of HCO_3^- uptake

Table 2

FTIR absorbance ratios of proteins to lipids, proteins to carbohydrates and lipids to carbohydrates in cells grown in the presence of either replete or ambient NO_3^- concentrations. Values represent an average of triplicates (\pm SD), except for the ratios of proteins to lipids, for which $n = 4$. Please note that values of the ratios based on FTIR spectroscopy measurements represent absorbance ratios and not amount ratios.

NO_3^- (μM)	Proteins to lipids ratio	Proteins to carbohydr. ratio (10^{-4})	Lipids to carbohydr. ratio (10^{-5})
Replete	15.5 ± 1.22	2.38 ± 0.54	1.3 ± 0.1
Ambient	11.6 ± 2.26	2.72 ± 0.65	3.0 ± 0.8

Table 3

Kinetics V_{max} and K_m of NR, NiR and GS, as well as GOGAT V_{max} in cells grown at replete and ambient NO_3^- . All values represent the means of triplicates (\pm SD). In the kinetics of GS for NH_2OH ($n = 4$).

NO_3^- (μM)			Replete	Ambient
NR	V_{max}	$\text{fmol NO}_2^- \text{ min}^{-1} \text{ cell}^{-1}$	1.09 ± 0.25	0.64 ± 0.06
	K_m (NO_3^-)	mM	0.099 ± 0.013	0.074 ± 0.007
NiR	V_{max}	$\text{fmol NO}_2^- \text{ min}^{-1} \text{ cell}^{-1}$	0.56 ± 0.05	0.3 ± 0.01
	K_m (NO_2^-)	mM	3.14 ± 0.6	1.69 ± 0.43
GS	V_{max}	$\text{fmol hydroxamate min}^{-1} \text{ cell}^{-1}$	0.385 ± 0.11	0.57 ± 0.04
	K_m (Glu)	mM	3.812 ± 1.63	1.621 ± 0.372
	K_m (NH_2OH)	mM	0.095 ± 0.035	0.092 ± 0.023
GOGAT	V_{max}	$\text{fmol NADH min}^{-1} \text{ cell}^{-1}$	2.87 ± 0.18	3.91 ± 0.76

decreased, the affinity of HCO_3^- uptake increased in cells grown at ambient NO_3^- (Table 4; Table S1). The rate of respiration expressed on a per cell basis was similar in high and low NO_3^- -grown cells (Table 4; Table S1). When respiration was expressed on organic C or cell volume basis, its rate was higher in cells at ambient NO_3^- .

4. Discussion

Although C and N quotas and cell volume were lower at ambient than at replete NO_3^- , growth rates and C to N ratios were similar for the two growth regimes used for this study (Table 1). The constant C to N ratio and the results obtained by FTIR spectroscopy suggest that the abundance of protein relative to the non-nitrogenous pools examined (i.e. carbohydrates and lipids) was not affected by the ambient NO_3^- treatment, and the lower protein content was simply the consequence of the lower C and N quotas. However, a shift occurred in the C partitioning between lipids and carbohydrates: the fraction of C allocated to lipids was appreciably higher than that located to carbohydrates (which became less abundant), when NO_3^- availability was lower (Table 2). A similar allocation pattern was also observed for cells of the marine diatom *Chaetoceros muellerii* by Giordano et al. (2001). The greater proportional allocation of C to lipids than to carbohydrates at ambient NO_3^- occurred together with a higher respiration rate (on an organic C and volume basis) measured in ambient NO_3^- -grown cells. Lipid biosynthesis would in fact require more energy and TCA cycle intermediates than carbohydrate production (Norici and Giordano, 2002; Montechiaro and Giordano, 2009). The shift of cell composition towards a higher lipid content relative to carbohydrate, in low NO_3^- -grown cells, may be related to the fact that these smaller cells benefit from the higher volume-, C- and mass-based energy content of lipid (Schmidt-Nielsen, 1997; Raven, 2005). The observed macromolecular composition may also have contributed to

Table 4

Kinetics V_{max} and $K_{1/2}$ of net photosynthesis, maximum light use efficiency of photosynthesis (α), kinetics of gross CO_2 uptake, net CO_2 uptake and HCO_3^- uptake, as well as respiration in cells grown at replete and ambient NO_3^- . For net photosynthesis, gross and net CO_2 uptake, HCO_3^- uptake and respiration in cells grown at replete NO_3^- ($n = 5$). All other values represent the means of triplicates (\pm SD).

NO_3^- (μM)			Replete	Ambient
Net photosynthesis	V_{max}	$\text{fmol O}_2 \text{ min}^{-1} \text{ cell}^{-1}$	12.9 ± 0.7	6.5 ± 0.8
	$K_{1/2}$ (CO_2)	μM	4.1 ± 0.6	2.5 ± 0.6
	$K_{1/2}$ (DIC)	μM	443 ± 79	263 ± 57
α		$\mu\text{mol O}_2 \text{ (mg Chl } a)^{-1} \text{ h}^{-1}$ ($\mu\text{mol photon m}^{-2} \text{ s}^{-1}$) ⁻¹	1.5 ± 0.04	1.7 ± 0.4
Gross CO_2 uptake	V_{max}	$\text{fmol CO}_2 \text{ min}^{-1} \text{ cell}^{-1}$	6.2 ± 2	5.4 ± 2
	$K_{1/2}$ (CO_2)	μM	3.5 ± 0.4	2.6 ± 0.8
Net CO_2 uptake	V_{max}	$\text{fmol CO}_2 \text{ min}^{-1} \text{ cell}^{-1}$	2.05 ± 0.4	2.8 ± 0.5
	$K_{1/2}$ (CO_2)	μM	4.5 ± 2	4.3 ± 0.6
HCO_3^- uptake	V_{max}	$\text{fmol HCO}_3^- \text{ min}^{-1} \text{ cell}^{-1}$	8.1 ± 3.1	2.8 ± 0.8
	$K_{1/2}$ (HCO_3^-)	μM	524 ± 180	195 ± 38
Respiration		$\text{fmol O}_2 \text{ min}^{-1} \text{ cell}^{-1}$	2.3 ± 0.4	1.9 ± 0.1

the decreased calcite content (Table 1) and higher proportion of incomplete coccoliths (Figs. 2 and 3) observed for low NO_3^- -grown cells. It has been hypothesized that, under N-deficiency, incomplete coccolith formation may be caused by a shortage of polysaccharides involved in coccolithogenesis and/or to "an inadequate level of some essential N-compound" (e.g. protein) that may affect crystal growth (Paasche, 1998). It is conspicuous that no differences in the percentages of malformed coccoliths were observed (Fig. 3). It is concluded that N-deficiency does not disturb the coccolith-shaping machinery as such. Two components of this machinery have been identified, namely the Coccolith Associated Polysaccharide, CAP (Henriksen et al., 2004; Marsh et al., 2002) and the cytoskeleton (Langer et al., submitted for publication). Hence, the shortage of polysaccharides, hypothesized by Paasche (1998), does not include CAP, nor does the shortage of protein include the cytoskeleton.

Based on the enzyme kinetics measured for NR and the kinetics of net photosynthesis derived from the MIMS measurements, we estimated the intracellular concentrations of NO_3^- and CO_2 which allow for balanced growth, i.e. maintenance of a constant C to N ratio. Please note that C and N fluxes based on MIMS measurements and NR activity represent instantaneous rates obtained three to four hours after the beginning of the photoperiod, while the C and N quotas represent integrated values over a complete LD cycle. For *E. huxleyi*, no significant differences were found between the integrated C to N ratios during exponential growth under continuous light and the ones under LD cycle (Price et al., 1998). During growth under continuous light, fixation of C and N appear to be closely coupled, hence the primary products of photosynthesis are directly used in biosynthesis rather than for carbon storage (Burkhardt et al., 1999). Under these circumstances, the net fixation rate of C (C_{flux}) can thus be expressed in terms of the N assimilation rate (N_{flux}), using the C to N ratio:

$$\frac{C_{\text{flux}}}{N_{\text{flux}}} = \frac{\text{POC}}{\text{PON}} \quad (1)$$

The upper boundary for C_{flux} in balance with N assimilation is provided by the maximum NR activity $V_{\text{max}}^{\text{NR}}$ and would be obtained at infinite NO_3^- concentration in the cytosol. Using our result for $V_{\text{max}}^{\text{NR}}$, the upper limit for C_{flux} that derives from Eq. (1) is very similar to the maximum net photosynthesis (in terms of C), which we obtained from the MIMS measurements ($V_{\text{max}}^{\text{CO}_2} = V_{\text{max}}^{\text{O}_2}/\text{PQ}$, with PQ being the photosynthetic quotient). For balanced growth to be maintained (Eq. (1)), the upper limit for C_{flux} must assume a value of $9.3 \text{ fmol min}^{-1} \text{ cell}^{-1}$ for the replete NO_3^- condition ($\text{POC}/\text{PON} = 8.5$), and $5.3 \text{ fmol min}^{-1} \text{ cell}^{-1}$ for cells acclimated to ambient NO_3^- ($\text{POC}/\text{PON} = 8.3$). Given the photosynthetic quotient from a NO_3^- -utilizing cell ($\text{PQ} = 1.36$; Williams and Robertson, 1991), the MIMS measurements predict a $V_{\text{max}}^{\text{CO}_2}$ of $9.5 \pm 0.5 \text{ fmol min}^{-1} \text{ cell}^{-1}$ and $4.8 \pm 0.6 \text{ fmol min}^{-1} \text{ cell}^{-1}$, for the replete and ambient NO_3^- conditions, respectively. Hence, the ratios of $V_{\text{max}}^{\text{CO}_2}$ and $V_{\text{max}}^{\text{NR}}$ are approximately given by the C to N ratios for the two growth NO_3^- concentrations used for this study (high NO_3^- : 1.0 POC/PON, low NO_3^- : 0.9 POC/PON). Using Eq. (1) and $V_{\text{max}}^{\text{CO}_2}/V_{\text{max}}^{\text{NR}} \approx \text{POC}/\text{PON}$ it follows that

$$\frac{C_{\text{flux}}}{V_{\text{max}}^{\text{CO}_2}} \approx \frac{N_{\text{flux}}}{V_{\text{max}}^{\text{NR}}} \quad (2)$$

In the following, we assume for the C_{flux} the enzyme activity of Rubisco and for the N_{flux} the enzyme activity of NR. Using Michaelis-Menten kinetics for the C and N fluxes, Eq. (2) yields the condition for balanced growth in terms of the intracellular concentrations of NO_3^- and CO_2

$$\frac{[\text{CO}_2]}{K_{\text{Rub}} + [\text{CO}_2]} \approx \frac{[\text{NO}_3^-]}{K_{\text{NR}} + [\text{NO}_3^-]} \quad (3)$$

which can be written as

$$\left(\frac{K_{\text{Rub}}}{[\text{CO}_2]} + 1 \right)^{-1} \approx \left(\frac{K_{\text{NR}}}{[\text{NO}_3^-]} + 1 \right)^{-1} \quad (4)$$

Finally, a further simplification of (4) yields

$$\frac{[\text{CO}_2]}{K_{\text{Rub}}} \approx \frac{[\text{NO}_3^-]}{K_{\text{NR}}} \quad (5)$$

with K_{Rub} and K_{NR} being the Michaelis-Menten constants for Rubisco and NR, respectively.

Generally, for an enzyme possessing the activity V_0 , the ratio of the concentration of the substrate S and the Michaelis-Menten constant K_m determines the degree of saturation of the enzyme activity ($V_0/V_{\text{max}} = 1/(K_m/[S] + 1)$). Based on Eq. (5) it follows that a constant C to N ratio can be maintained for intracellular $[\text{CO}_2]$ and $[\text{NO}_3^-]$ which yield a comparable saturation of the enzyme activity for the enzymes involved in C and N assimilation. Hence, the maintenance of a constant C to N ratio requires a concerted regulation of the intracellular $[\text{CO}_2]$ and $[\text{NO}_3^-]$ to equilibrate the fluxes through the C and N assimilation pathway. It should be noted that Eq. (5) is valid for all degrees of enzyme saturation ($0 < V_0/V_{\text{max}} < 1$) in the cells acclimated to the two growth regimes. This flexibility indicates that the maintenance of a constant C to N ratio under different growth conditions does not imply constant kinetic properties of the enzymes involved in the C and N assimilation pathway. In fact, the availability of NO_3^- affects the kinetics of NR, NiR and net photosynthesis in *E. huxleyi* cells. At ambient NO_3^- , the V_{max} of NR, NiR and net photosynthesis was down-regulated compared to cells grown at replete NO_3^- (Tables 3 and 4), probably as a result of less protein amounts. In cells grown at ambient NO_3^- , the effect of lower enzyme activity (V_{max}) on the C and N flux was weakened by the increase in the affinity of NR, NiR and net photosynthesis for the substrates (Tables 3 and 4). Since the *E. huxleyi* genome appears to have only one gene encoding for NR (Bruhn et al., 2010) and one encoding for NiR (Wurch), the change in the affinity for the substrates (lower K_m of NR for NO_3^- and of NiR for NO_2^- at ambient NO_3^-) cannot be attributed to the expression of different isoforms and must be attributed to post-translational regulation. The decrease in the $K_{1/2}$ of photosynthesis at ambient NO_3^- may be related to post-translational regulation or expression of high-affinity HCO_3^- transporters (Amoroso et al., 2003). The kinetics of GS in *E. huxleyi* cells are also modified in response to NO_3^- availability. The higher total GS V_{max} in cells at ambient NO_3^- (Table 3) may be a response of NH_4^+ re-assimilation after increased proteolysis in cells under N limiting conditions (Hipkin et al., 1982). The activity of GOGAT showed more or less the same response to NO_3^- availability as total GS activity; this is not surprising, since these two enzymes operate sequentially.

In addition to the regulation of K_m , the degree of enzyme saturation is determined by the substrate concentration established at the site of the enzyme. For instance, when the NR activity reaches 80% of its maximum value, NO_3^- accumulates in the cytosol, yielding concentrations of 396 μM and 296 μM for the cells acclimated to high and low NO_3^- , respectively. For balanced growth to be maintained (Eq. (5)), the CO_2 concentration at the site of Rubisco must then exceed K_{Rub} by a factor of 4, for the replete and ambient NO_3^- conditions. The values of K_{Rub} for the two growth conditions are not known. Assuming a K_{Rub} of 30 μM (Badger et al., 1998), it follows a $[\text{CO}_2]$ at Rubisco of 120 μM . We assumed steady state conditions for N assimilation. In other words, the substrates inside the cell accumulate until the rates of reactions are the same for all the

enzymes involved in the N assimilation pathway (from NO_3^- to NH_4^+ assimilation by GS):

$$N_{\text{flux}} = \frac{V_{\text{max}}^{\text{NR}}[\text{NO}_3^-]}{K_{\text{NR}} + [\text{NO}_3^-]} = \frac{V_{\text{max}}^{\text{NiR}}[\text{NO}_2^-]}{K_{\text{NiR}} + [\text{NO}_2^-]} = \frac{V_{\text{max}}^{\text{GS}}[\text{NH}_4^+]}{K_{\text{GS}} + [\text{NH}_4^+]} \quad (6)$$

Then, the NiR kinetics data predicts an accumulation of high NO_2^- concentrations at the site of NiR activity. The requirement for a high NO_2^- concentration for *E. huxleyi* NiR suggests that this enzyme is confined in the proximity of the chloroplast envelope, possibly near the entry point of NO_2^- into the chloroplast. However, high internal NO_2^- pools of 4 to 5 mM have been reported for the diatom *Chaetocheros* sp. (Lomas and Glibert, 2000).

The GS could not be used for estimated intracellular NH_4^+ concentrations in our study. Glutamine synthetase activity was found to be approximately 40% higher when measured with a radioactive assay with ammonia as substrate in comparison to the colorimetric assay with NH_2OH as substrate (Listrom et al., 1997). Furthermore, GS activity in microalgae deriving from measurements with the biosynthetic reaction assay was found to be two to three fold higher compared with the enzyme activity from the transferase reaction assay (Bressler and Ahmed, 1984). Therefore the use of NH_2OH instead of NH_4^+ and/or the application of the GS transferase instead of the biosynthetic assay may be the reasons that do not allow using GS V_{max} for the estimation of intracellular NH_4^+ concentrations in our study.

In conclusion, NO_3^- availability seem to have a crucial impact on the regulation of C and N fluxes in the marine coccolithophore *E. huxleyi*, without necessarily changing the C to N ratios and/or growth rates of cells. With the exception of GS and GOGAT, cells generally respond to ambient NO_3^- availability with a down regulation of activities of proteins involved in the acquisition and assimilation of inorganic C and N. At the same time, the substrate affinities of these proteins increase in response to ambient NO_3^- . Our study suggests that the intracellular CO_2 and NO_3^- concentrations have to be carefully regulated, in order to equilibrate the fluxes through the C and N assimilation pathways, and ensure an adequate growth for the respective NO_3^- conditions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jembe.2010.06.004.

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