

# Combined Effects of CO<sub>2</sub> and Light on the N<sub>2</sub>-Fixing Cyanobacterium *Trichodesmium* IMS101: Physiological Responses<sup>1[OA]</sup>

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Recent studies on the diazotrophic cyanobacterium *Trichodesmium erythraeum* (IMS101) showed that increasing CO<sub>2</sub> partial pressure (pCO<sub>2</sub>) enhances N<sub>2</sub> fixation and growth. Significant uncertainties remain as to the degree of the sensitivity to pCO<sub>2</sub>, its modification by other environmental factors, and underlying processes causing these responses. To address these questions, we examined the responses of *Trichodesmium* IMS101 grown under a matrix of low and high levels of pCO<sub>2</sub> (150 and 900 μatm) and irradiance (50 and 200 μmol photons m<sup>-2</sup> s<sup>-1</sup>). Growth rates as well as cellular carbon and nitrogen contents increased with increasing pCO<sub>2</sub> and light levels in the cultures. The pCO<sub>2</sub>-dependent stimulation in organic carbon and nitrogen production was highest under low light. High pCO<sub>2</sub> stimulated rates of N<sub>2</sub> fixation and prolonged the duration, while high light affected maximum rates only. Gross photosynthesis increased with light but did not change with pCO<sub>2</sub>. HCO<sub>3</sub><sup>-</sup> was identified as the predominant carbon source taken up in all treatments. Inorganic carbon uptake increased with light, but only gross CO<sub>2</sub> uptake was enhanced under high pCO<sub>2</sub>. A comparison between carbon fluxes in vivo and those derived from <sup>13</sup>C fractionation indicates high internal carbon cycling, especially in the low-pCO<sub>2</sub> treatment under high light. Light-dependent oxygen uptake was only detected under low pCO<sub>2</sub> combined with high light or when low-light-acclimated cells were exposed to high light, indicating that the Mehler reaction functions also as a photoprotective mechanism in *Trichodesmium*. Our data confirm the pronounced pCO<sub>2</sub> effect on N<sub>2</sub> fixation and growth in *Trichodesmium* and further show a strong modulation of these effects by light intensity. We attribute these responses to changes in the allocation of photosynthetic energy between carbon acquisition and the assimilation of carbon and nitrogen under elevated pCO<sub>2</sub>. These findings are supported by a complementary study looking at photosynthetic fluorescence parameters of photosystem II, photosynthetic unit stoichiometry (photosystem I:photosystem II), and pool sizes of key proteins in carbon and nitrogen acquisition.

Human-induced climate change will significantly alter the marine environment within the next century and beyond. Future scenarios predict an increase from currently approximately 380 to about 750 to 1,000 μatm CO<sub>2</sub> partial pressure (pCO<sub>2</sub>) in the atmosphere until the end of this century (Raven et al., 2005; Raupach et al., 2007). As the ocean takes up this

anthropogenic CO<sub>2</sub>, dissolved inorganic carbon (DIC) in the surface ocean increases while the pH decreases (Wolf-Gladrow et al., 1999). Rising global temperatures will increase surface ocean stratification, which may affect the light regime in the upper mixed layer as well as nutrient input from deeper waters (Doney, 2006). Uncertainties remain regarding both the magnitude of the physicochemical changes and the biological responses of organisms, including species and populations of the oceanic primary producers at the basis of the food webs.

In view of potential ecological implications and feedbacks on climate, several studies have examined pCO<sub>2</sub> sensitivity in phytoplankton key species (Burkhardt and Riebesell, 1997; Riebesell et al., 2000; Rost et al., 2003; Tortell et al., 2008). Pronounced responses to elevated pCO<sub>2</sub> were observed in N<sub>2</sub>-fixing cyanobacteria (Barcelos é Ramos et al., 2007; Hutchins et al., 2007; Levitan et al., 2007; Fu et al., 2008; Kranz et al., 2009), which play a vital role in marine ecosystems by providing a new source of biologically available nitrogen species to otherwise nitrogen-limited regions. Recent studies focused on the impact of different environmental factors on the filamentous *Trichodesmium* species, which is

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known for high abundance and the formation of massive blooms in tropical and subtropical areas (Capone et al., 2005; Mahaffey et al., 2005). Higher pCO<sub>2</sub> levels stimulated growth rates, biomass production, and N<sub>2</sub> fixation (Hutchins et al., 2007; Levitan et al., 2007; Kranz et al., 2009) and affected inorganic carbon acquisition of the cells (Kranz et al., 2009). While elevated sea surface temperatures are predicted to shift the spatial distribution of *Trichodesmium* species toward higher latitudes (Breitbart et al., 2007), the combined effects of pCO<sub>2</sub> and temperature may favor this species and extend its niche even farther (Hutchins et al., 2007; Levitan et al., 2010a). An increase in the average light intensity, caused by the predicted shoaling of the upper mixed layer, may further stimulate photosynthesis and thus growth and N<sub>2</sub> fixation of *Trichodesmium* (Breitbart et al., 2008). To our knowledge, the combined effects of light and pCO<sub>2</sub> have not been studied yet, although these environmental factors are likely to influence photosynthesis and other key processes in *Trichodesmium*.

To understand the responses of an organism to changes in environmental conditions, metabolic processes must be studied. In *Trichodesmium*, photosynthetically generated energy (ATP and NADPH) is primarily used for the fixation of CO<sub>2</sub> in the Calvin-Benson cycle. A large proportion of this energy, however, is also required for the process of N<sub>2</sub> fixation via nitrogenase and for the operation of a CO<sub>2</sub>-concentrating mechanism (CCM). The latter involves active uptake of inorganic carbon, which functions to increase the rate of carboxylation reaction mediated by Rubisco. This ancient and highly conserved enzyme is characterized by low affinities for its substrate CO<sub>2</sub> and a susceptibility to a competing reaction with oxygen (O<sub>2</sub>) as substrate (Badger et al., 1998); the latter initiates photorespiration. As cyanobacterial Rubisco possesses one of the lowest CO<sub>2</sub> affinities among phytoplankton (Badger et al., 1998), a considerable amount of resources have to be invested to achieve sufficient rates of carbon fixation and to avoid photorespiration. A first step toward a mechanistic understanding of responses in *Trichodesmium* has been taken by Levitan et al. (2007), focusing on pCO<sub>2</sub> dependency of nitrogenase activity and photosynthesis. Subsequently, Kranz et al. (2009) described variations in CCM efficiency with pCO<sub>2</sub> and suggested that the observed plasticity in CCM regulation allowed energy reallocation under high pCO<sub>2</sub>, which may explain the observed pCO<sub>2</sub>-dependent changes in nitrogenase activity, growth, and elemental composition (Barcelos é Ramos et al., 2007; Hutchins et al., 2007; Levitan et al., 2007).

In this study, we measured growth responses as well as metabolic key processes in *Trichodesmium erythraeum* (IMS101) under environmental conditions that likely alter the energy budget and/or energy allocation of the cell. Cultures were acclimated to a matrix of low and high pCO<sub>2</sub> (150 and 900 μatm) at two different light intensities (50 and 200 μmol photons m<sup>-2</sup> s<sup>-1</sup>). For each of the four treatments, changes in growth

rates, elemental ratios, and the accumulation of particulate carbon and nitrogen were measured. Metabolic processes (gross photosynthesis, CCM activity, and O<sub>2</sub> uptake) were obtained by means of membrane-inlet mass spectrometry (MIMS), while N<sub>2</sub> fixation was detected by gas chromatography. As these processes may vary over the diurnal cycle in *Trichodesmium* (Berman-Frank et al., 2001; Kranz et al., 2009), measurements were performed in the morning and around midday. The results on metabolic processes were accompanied by measurements of the fluorescence of PSII, ratios of the photosynthetic units (PSI:PSII), and pool sizes of key proteins involved in carbon and nitrogen fixation as well as assimilation (Levitan et al., 2010b).

## RESULTS

### Elemental Composition, and Growth and Production Rates

Cellular quotas of particulate organic carbon (POC) and particulate organic nitrogen (PON) increased with both pCO<sub>2</sub> and light, while particulate phosphorus (PP) quotas remained constant in all treatments (one-way ANOVA for PP;  $P > 0.05$ ; Table I). POC quota ranged between  $3.79 \pm 0.09$  and  $4.51 \pm 0.21$  pmol cell<sup>-1</sup> under low light and  $4.60 \pm 0.46$  and  $5.02 \pm 0.57$  pmol cell<sup>-1</sup> under high light (Table I). Elevated pCO<sub>2</sub> significantly increased the POC cell<sup>-1</sup> by 19% at low light ( $t$  test;  $P = 0.001$ ) and by 9% (although not significant) at high light ( $t$  test;  $P = 0.226$ ). PON quotas exhibited similar patterns, with values ranging from  $0.59 \pm 0.03$  to  $0.88 \pm 0.06$  pmol cell<sup>-1</sup> under low light and  $0.86 \pm 0.08$  to  $1.04 \pm 0.09$  pmol cell<sup>-1</sup> under high light at low and high pCO<sub>2</sub>, respectively (Table I). The pCO<sub>2</sub>-dependent changes in the PON quota were even larger than those of the POC, with a significant increase by 47% under low light ( $t$  test;  $P < 0.001$ ) and 21% under high light ( $t$  test;  $P < 0.05$ ). Respective carbon-nitrogen ratios decreased from  $6.41 \pm 0.39$  to  $5.04 \pm 0.15$  under low light (one-way ANOVA followed by a posthoc test;  $P < 0.05$ ) and from  $5.25 \pm 0.19$  to  $4.85 \pm 0.10$  under high light with increasing pCO<sub>2</sub> (one-way ANOVA followed by a posthoc test;  $P = 0.09$ ; Table I). Chlorophyll *a* (chl *a*) cell<sup>-1</sup> did not differ significantly between treatments, excluding cells grown under low light and low pCO<sub>2</sub> (one-way ANOVA followed by a posthoc test;  $P < 0.001$ ; Table I).

Growth increased significantly with both elevated pCO<sub>2</sub> and higher light (one-way ANOVA followed by a posthoc test;  $P < 0.001$ ). There was no difference between growth rate estimates whether based on changes in cell densities, chl *a*, POC, or PON; thus, they are reported as mean values. Growth rates ranged between  $0.15 \pm 0.03$  and  $0.24 \pm 0.03$  d<sup>-1</sup> at low light and from  $0.38 \pm 0.02$  to  $0.42 \pm 0.02$  d<sup>-1</sup> at high light (Fig. 1A). Elevated pCO<sub>2</sub> increased growth rates by 60% under low light and by 11% under high light. Rates of POC production also increased significantly under elevated pCO<sub>2</sub> ( $t$  test;  $P < 0.001$ ), ranging

**Table I.** Elemental composition of *Trichodesmium IMS101* under a matrix of pCO<sub>2</sub> and lightValues represent means of triplicate cultures, sampled over several days, all within exponential phase. Errors are ±1 sd (*n* > 10).

Elemental Composition	Acclimation			
	Low Light (50 μmol Photons m <sup>-2</sup> s <sup>-1</sup> )		High Light (200 μmol Photons m <sup>-2</sup> s <sup>-1</sup> )	
	150 μatm pCO <sub>2</sub>	900 μatm pCO <sub>2</sub>	150 μatm pCO <sub>2</sub>	900 μatm pCO <sub>2</sub>
POC (pmol carbon cell <sup>-1</sup> ) <sup>a</sup>	3.79 ± 0.09	4.51 ± 0.21	4.60 ± 0.46	5.02 ± 0.57
PON (pmol nitrogen cell <sup>-1</sup> ) <sup>a</sup>	0.59 ± 0.03	0.88 ± 0.06	0.86 ± 0.08	1.04 ± 0.09
PP (fmol phosphorus cell <sup>-1</sup> )	73 ± 9	78 ± 9	70 ± 14	71 ± 4
Chl a (pg cell <sup>-1</sup> ) <sup>b</sup>	0.47 ± 0.04	0.72 ± 0.05	0.67 ± 0.14	0.69 ± 0.08
Carbon:nitrogen (mol:mol) <sup>c</sup>	6.41 ± 0.39	5.04 ± 0.15	5.25 ± 0.19	4.85 ± 0.10

<sup>a</sup>*t* test: significant difference between high-light acclimations. <sup>b</sup>*t* test: significant difference between low-light acclimations. <sup>c</sup>One-way ANOVA: significant difference between all acclimations.

between  $0.57 \pm 0.11$  and  $1.10 \pm 0.17$  pmol carbon cell<sup>-1</sup> d<sup>-1</sup> under low light and between  $1.76 \pm 0.26$  and  $2.12 \pm 0.34$  pmol carbon cell<sup>-1</sup> d<sup>-1</sup> under high light (Fig. 1B). The PON production increased under elevated pCO<sub>2</sub> (*t* test; *P* < 0.001), ranging between  $0.09 \pm 0.02$  and  $0.21 \pm 0.04$  pmol nitrogen cell<sup>-1</sup> d<sup>-1</sup> under low light and between  $0.33 \pm 0.05$  and  $0.44 \pm 0.06$  pmol nitrogen cell<sup>-1</sup> d<sup>-1</sup> under high light (Fig. 1C). Notably, at low light, elevated pCO<sub>2</sub> caused the strongest relative increase in POC and PON production, being 93% and 133% higher than under low pCO<sub>2</sub>, respectively.

## N<sub>2</sub> Fixation

Both the diurnal pattern and the rates of N<sub>2</sub> fixation responded strongly to pCO<sub>2</sub> and light (Fig. 2). For the low-light acclimations, N<sub>2</sub> fixation peaked 3 h after the beginning of the photoperiod with maximum rates, which range between  $1.61 \pm 0.51$  and  $3.03 \pm 0.56$  μmol N<sub>2</sub> mg chl a<sup>-1</sup> h<sup>-1</sup> for low and high pCO<sub>2</sub>, respectively. Under high light, both pCO<sub>2</sub> acclimations peaked about 5 h after the onset of light, and maximum rates were  $15.45 \pm 1.29$  and  $19.21 \pm 6.48$  μmol N<sub>2</sub> mg chl a<sup>-1</sup> h<sup>-1</sup> for the low and high pCO<sub>2</sub> treatments, respectively (Fig. 2A). Elevated pCO<sub>2</sub> increased maximum rates about 2-fold under low light, while maximum rates appear not to differ at high light. More prominently, under high light, elevated pCO<sub>2</sub> led to a prolonged phase with high N<sub>2</sub> fixation rates, which lasted until the end of the photoperiod. This pCO<sub>2</sub> effect on the diurnal cycle was also present but less pronounced under low light. No N<sub>2</sub> fixation occurred during the dark period in all acclimations. As a result of the higher fixation rates and the prolonged N<sub>2</sub> fixation under elevated pCO<sub>2</sub>, the integrated diurnal values of N<sub>2</sub> fixation increased by 200% and 112% under low and high light, respectively (Fig. 2B).

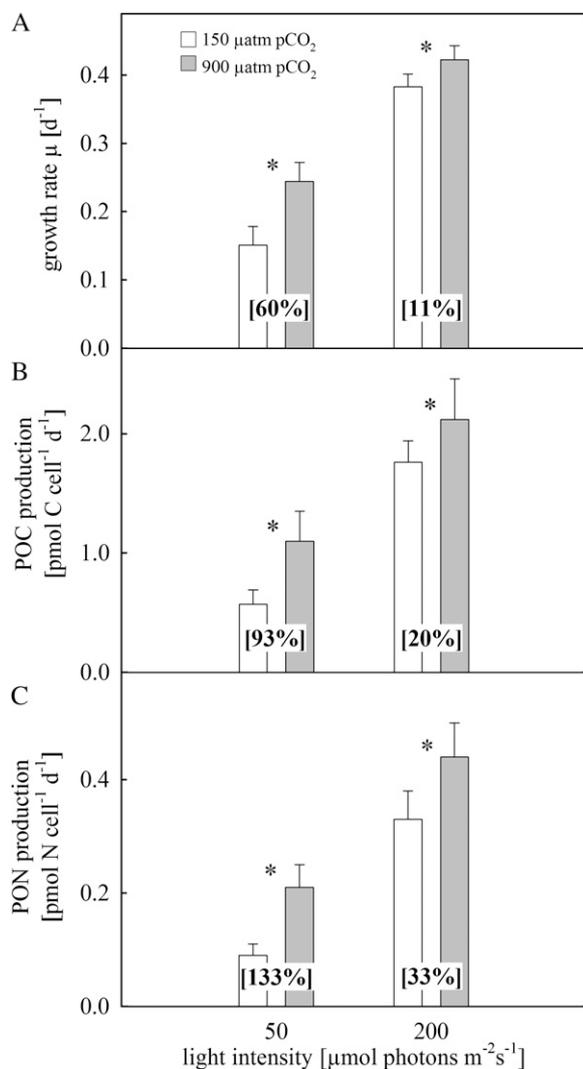
## Photosynthetic O<sub>2</sub> Evolution and O<sub>2</sub> Uptake

Gross O<sub>2</sub> evolution increased with light but was neither affected by pCO<sub>2</sub> nor varied among measurements performed between 2 to 3 h (AM) and 6 to 7 h (PM) after the beginning of the photoperiod (Fig. 3A;

Table II). O<sub>2</sub> evolution ranged between  $119 \pm 22$  and  $156 \pm 4$  μmol O<sub>2</sub> mg chl a<sup>-1</sup> h<sup>-1</sup> at low light and between  $432 \pm 153$  and  $534 \pm 51$  μmol O<sub>2</sub> mg chl a<sup>-1</sup> h<sup>-1</sup> at high light (Fig. 3A; Table II). O<sub>2</sub> uptake in the light was present in all treatments (Fig. 3B), yet rates were, with one exception, similar to those determined in the dark (Table II). At 150 μatm pCO<sub>2</sub> and 200 μmol photons m<sup>-2</sup> s<sup>-1</sup>, O<sub>2</sub> uptake in the light significantly exceeded dark respiration by about 140% in the morning and by about 70% during midday (*t* test; *P* < 0.001; Table II). Light-dependent O<sub>2</sub> uptake was also induced when cells acclimated to 50 μmol photons m<sup>-2</sup> s<sup>-1</sup> were exposed to 200 μmol photons m<sup>-2</sup> s<sup>-1</sup> during the measurements, irrespective of the pCO<sub>2</sub> level of the acclimation (Table II). Such instantaneous effects were also observed in the gross O<sub>2</sub> evolution (i.e. low-light-acclimated cells exposed to high light yielded rates similar to cells that had been acclimated to high light).

## Inorganic Carbon Acquisition and Leakage

HCO<sub>3</sub><sup>-</sup> was the major inorganic carbon source taken up by *Trichodesmium* in all acclimations, while CO<sub>2</sub> contributed only a minor fraction. Rates of HCO<sub>3</sub><sup>-</sup> uptake were affected by both light and pCO<sub>2</sub>, ranging from  $82 \pm 19$  to  $121 \pm 25$  μmol HCO<sub>3</sub><sup>-</sup> mg chl a<sup>-1</sup> h<sup>-1</sup> in low light and from  $224 \pm 30$  to  $287 \pm 50$  μmol HCO<sub>3</sub><sup>-</sup> mg chl a<sup>-1</sup> h<sup>-1</sup> in high light at low and high pCO<sub>2</sub>, respectively (Table III). Under low light, HCO<sub>3</sub><sup>-</sup> uptake decreased slightly, although not significantly, when cultures were acclimated to high pCO<sub>2</sub> (one-way ANOVA followed by a posthoc test; *P* > 0.05). Under high light, HCO<sub>3</sub><sup>-</sup> uptake remained relatively stable at both pCO<sub>2</sub> levels. Rates of gross CO<sub>2</sub> uptake were affected by both light and pCO<sub>2</sub>, ranging between  $10 \pm 1$  and  $22 \pm 10$  μmol CO<sub>2</sub> mg chl a<sup>-1</sup> h<sup>-1</sup> in low light and between  $59 \pm 6$  and  $147 \pm 31$  μmol CO<sub>2</sub> mg chl a<sup>-1</sup> h<sup>-1</sup> at high light at low and high pCO<sub>2</sub>, respectively (Table II). To illustrate the contribution of each carbon species to the total carbon uptake, the ratio of HCO<sub>3</sub><sup>-</sup> uptake to gross CO<sub>2</sub> uptake is depicted in Figure 4. Ratios ranged between 2 and 10, reflecting that HCO<sub>3</sub><sup>-</sup> was the major carbon species taken up in all treatments. The



**Figure 1.** Responses of *Trichodesmium* IMS101 to different light (50 and 200  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ ) and pCO<sub>2</sub> (150 and 900  $\mu\text{atm}$ ) levels. A, Growth rates. B, Production rates of POC. C, Production rates of PON. Numbers in brackets denote the relative increase from low to high pCO<sub>2</sub> levels. Asterisks between bars indicate significant differences between low and high pCO<sub>2</sub> levels (*t* test; *P* < 0.05). Error bars indicate 1 *sd* (*n* ≥ 10).

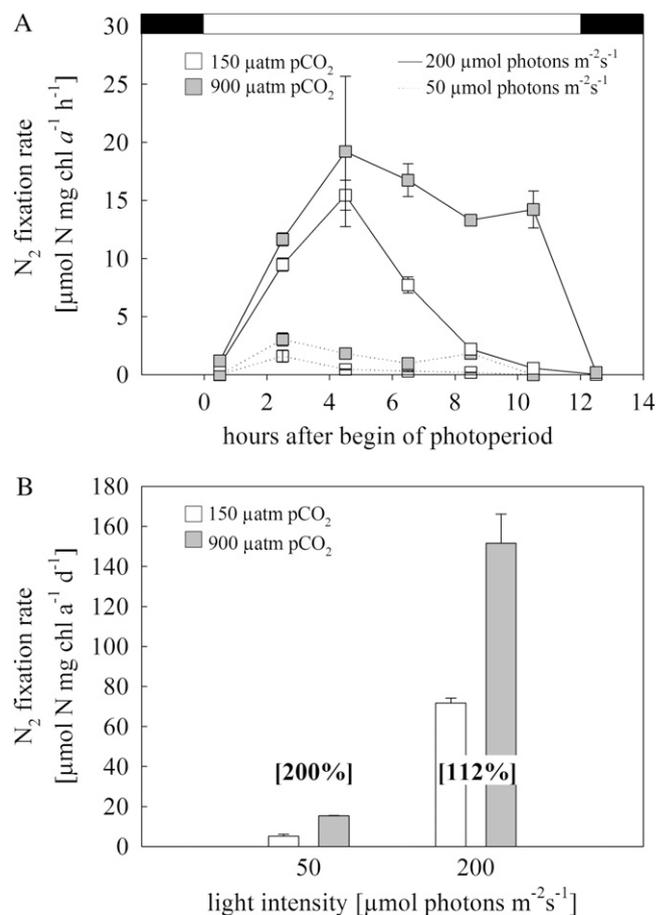
increased relevance of CO<sub>2</sub> uptake was indicated by the declining HCO<sub>3</sub><sup>-</sup>:CO<sub>2</sub> uptake ratios under elevated pCO<sub>2</sub> and high light (Fig. 4). Rates of net O<sub>2</sub> evolution obtained in these assays (data not shown) were similar to those obtained in the assays on O<sub>2</sub> fluxes (Table II).

Cellular leakage (CO<sub>2</sub> efflux:gross carbon uptake) determined by MIMS measurements was generally low under low pCO<sub>2</sub>, ranging between  $0.24 \pm 0.13$  and  $0.29 \pm 0.19$  in the low- and high-light acclimation, respectively (Table IV). In the high-pCO<sub>2</sub> acclimation, leakage was  $0.41 \pm 0.09$  and  $0.31 \pm 0.14$  in the low- and high-light acclimation, respectively. Leakage estimates deduced from <sup>13</sup>C fractionation were much higher than those measured directly by MIMS. In the low-

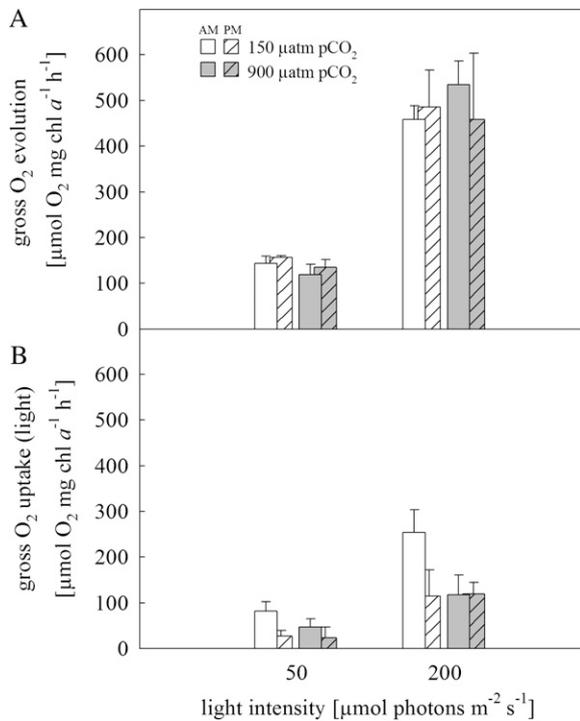
pCO<sub>2</sub> acclimations, leakage was  $0.57 \pm 0.02$  at high light and  $0.84 \pm 0.03$  at low light, and it was about 0.90 in both high-pCO<sub>2</sub> acclimations (Table IV). These leakage estimates were derived from <sup>13</sup>C fractionation ( $\epsilon_p$ ), ranging between  $12.94\% \pm 0.78\%$  and  $7.19\% \pm 0.58\%$  under low pCO<sub>2</sub> at low and high light, respectively. Higher  $\epsilon_p$  values were measured under elevated pCO<sub>2</sub>, being  $15.69\% \pm 1.12\%$  and  $16.54\% \pm 0.10\%$  at low and high light, respectively.

## DISCUSSION

The results of our study confirm the pronounced pCO<sub>2</sub> effect on N<sub>2</sub> fixation and growth in *Trichodesmium* and further show a strong modulation of these effects by irradiance. Cellular gas-exchange measurements revealed pCO<sub>2</sub>-dependent changes in rates of N<sub>2</sub> fixation over the course of the photoperiod as well as in modes of carbon acquisition. Taken together, our



**Figure 2.** A, Diurnal cycle of nitrogen fixation of *Trichodesmium* IMS101 at the different light and pCO<sub>2</sub> acclimations. Measurements were obtained from duplicate cultures. Error bars indicate 1 *sd*. The black and white areas at top correspond to the dark and light periods of the diurnal cycle. B, Integrated diurnal N<sub>2</sub> fixation rate from A. Numbers in brackets denote the relative increase from low to high pCO<sub>2</sub> levels. Error bars indicate 1 *sd* (*n* ≥ 2).



**Figure 3.**  $O_2$  fluxes of *Trichodesmium* IMS101 measured between 2 to 3 h (AM; plain bars) and 6 to 7 h (PM; striped bars) after the beginning of the photoperiod. A, Gross  $O_2$  evolution rate. B, Gross  $O_2$  uptake rate in the light. Error bars indicate 1 SD ( $n \geq 2$ ).

results indicate the reallocation of photosynthetic energy between both processes. Further evidence for this is presented in our complementary study (Levitan et al., 2010b).

#### Elemental Ratios, and Growth and Production Rates

*Trichodesmium* demonstrates high plasticity in growth and/or elemental composition with changing levels of  $pCO_2$  (Barcelos é Ramos et al., 2007; Hutchins et al.,

2007; Levitan et al., 2007; Kranz et al., 2009) and light (Breitbarth et al., 2008). The observed responses to these abiotic factors provide prima facie evidence for the increasing importance of *Trichodesmium* species in future oceans. In our study, the combined effect of  $pCO_2$  and light, two factors that are predicted to change in the future ocean, were studied on *Trichodesmium* IMS101 and are discussed on an ecophysiological level.

The elemental composition of *Trichodesmium* cells showed an increase in POC and PON quotas with enhanced  $pCO_2$  concentrations (Table I), a finding consistent with Kranz et al. (2009) but contradicting Barcelos é Ramos et al. (2007), who reported decreasing POC and PON quotas with elevated  $pCO_2$ . No  $pCO_2$ -dependent changes in elemental stoichiometry of carbon to nitrogen were observed in previous studies with light intensities between 80 and 150  $\mu mol photons m^{-2} s^{-1}$  (Barcelos é Ramos et al., 2007; Hutchins et al., 2007; Levitan et al., 2007; Kranz et al., 2009). However, under 50  $\mu mol photons m^{-2} s^{-1}$ , lower carbon-to-nitrogen ratios were obtained under elevated  $pCO_2$  (Table I), reflecting a greater  $pCO_2$  effect on the PON than on the POC quota under low light. Cell quotas for PP did not differ between acclimations (Table I), a finding that disagrees with decreasing organic phosphorus quotas under elevated  $pCO_2$  observed by Barcelos é Ramos et al. (2007). The  $pCO_2$ -dependent increases in carbon-to-phosphorus and/or nitrogen-to-phosphorus ratios observed in this and previous studies imply that more biomass can be produced per available phosphorus.

The observed increase in growth rates under elevated  $pCO_2$  (Fig. 1A) is consistent with previous findings from *Trichodesmium* (Barcelos é Ramos et al., 2007; Hutchins et al., 2007; Levitan et al., 2007). Yet, the magnitude in  $pCO_2$ -dependent stimulation differed strongly between studies and is probably associated with the different light intensities applied (approximately 80–150  $\mu mol photons m^{-2} s^{-1}$ ; Barcelos é Ramos et al., 2007; Hutchins et al., 2007; Levitan et al., 2007; Kranz et al., 2009). As our study focused

**Table II.**  $O_2$  fluxes in *Trichodesmium* IMS101 according to the method of Peltier and Thibault (1985)

Values represent rates measured between 2 to 3 h (AM) and 6 to 7 h (PM) after the beginning of the photoperiod. Blanks denote no measurement. Errors are  $\pm 1$  SD ( $n \geq 3$ ). No SD is given when only one measurement was obtained.

Oxygen Fluxes	Assay Condition	Acclimation				
		Low Light (50 $\mu mol$ Photons $m^{-2} s^{-1}$ )		High Light (200 $\mu mol$ Photons $m^{-2} s^{-1}$ )		
		150 $\mu atm$ $pCO_2$	900 $\mu atm$ $pCO_2$	150 $\mu atm$ $pCO_2$	900 $\mu atm$ $pCO_2$	
Gross $O_2$ evolution ( $\mu mol O_2$ $mg chl a^{-1} h^{-1}$ )	Low light	AM	143 $\pm$ 16	119 $\pm$ 22		
		PM	156 $\pm$ 4	135 $\pm$ 17		
	High light	AM	453	538 $\pm$ 70	454 $\pm$ 28	534 $\pm$ 51
		PM	612	429 $\pm$ 42	486 $\pm$ 81	432 $\pm$ 153
$O_2$ uptake in the light ( $\mu mol O_2$ $mg chl a^{-1} h^{-1}$ )	Low light	AM	81 $\pm$ 21	46 $\pm$ 18		
		PM	27 $\pm$ 12	23 $\pm$ 23		
	High light	AM	200	137 $\pm$ 33	254 $\pm$ 49	117 $\pm$ 42
		PM	81	83 $\pm$ 62	115 $\pm$ 57	123 $\pm$ 27
$O_2$ uptake in the dark ( $\mu mol O_2$ $mg chl a^{-1} h^{-1}$ )	No light	AM	115 $\pm$ 10	83 $\pm$ 11	106 $\pm$ 44	126 $\pm$ 30
		PM	25 $\pm$ 8	24 $\pm$ 7	67 $\pm$ 13	111 $\pm$ 24

**Table III.** Carbon fluxes in *Trichodesmium* IMS101 measured according to Badger et al. (1994)Values represent rates measured between 2 to 3 h (AM) and 6 to 7 h (PM) after the beginning of the photoperiod. Errors are  $\pm 1$  SD ( $n \geq 3$ ).

Inorganic Carbon Fluxes	Assay Condition	Acclimation				
		Low Light (50 $\mu\text{mol Photons m}^{-2} \text{s}^{-1}$ )		High Light (200 $\mu\text{mol Photons m}^{-2} \text{s}^{-1}$ )		
		150 $\mu\text{atm pCO}_2$	900 $\mu\text{atm pCO}_2$	150 $\mu\text{atm pCO}_2$	900 $\mu\text{atm pCO}_2$	
Net fixation ( $\mu\text{mol C mg chl a}^{-1} \text{h}^{-1}$ )	Same as acclimation	AM	98 $\pm$ 4	69 $\pm$ 7	301 $\pm$ 9	226 $\pm$ 55
		PM	92 $\pm$ 10	52 $\pm$ 8	330 $\pm$ 40	290 $\pm$ 15
HCO <sub>3</sub> <sup>-</sup> uptake ( $\mu\text{mol HCO}_3^- \text{mg chl a}^{-1} \text{h}^{-1}$ )	Same as acclimation	AM	105 $\pm$ 8	82 $\pm$ 19	247 $\pm$ 50	224 $\pm$ 30
		PM	121 $\pm$ 25	98 $\pm$ 8	287 $\pm$ 50	282 $\pm$ 28
CO <sub>2</sub> uptake ( $\mu\text{mol CO}_2 \text{mg chl a}^{-1} \text{h}^{-1}$ )	Same as acclimation	AM	10 $\pm$ 1	22 $\pm$ 10	59 $\pm$ 6	90 $\pm$ 19
		PM	17 $\pm$ 5	19 $\pm$ 6	61 $\pm$ 8	147 $\pm$ 31

on different pCO<sub>2</sub> levels in combination with low and high light, we could indeed verify that light levels strongly modify the responses of *Trichodesmium* to pCO<sub>2</sub> (Fig. 1; Table I). Like the responses in elemental composition, the relative changes in growth rates to elevated pCO<sub>2</sub> were largest under low light.

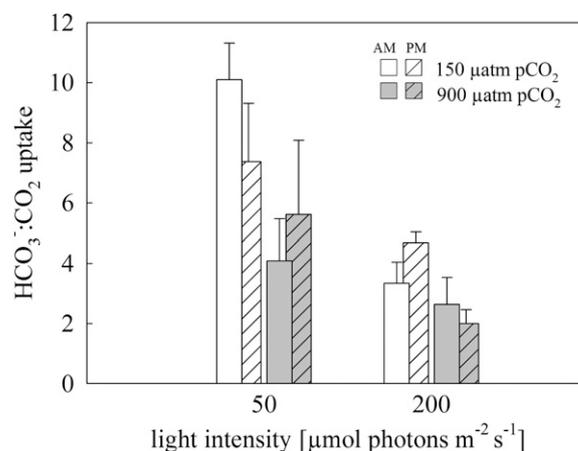
Due to the described effects on elemental composition and growth rates, the buildup of biomass in *Trichodesmium* increased strongly under elevated pCO<sub>2</sub> (Fig. 1, B and C). The pCO<sub>2</sub>-dependent stimulation was highest under low light, with a 93% increase for POC production and a 133% increase for PON production relative to low pCO<sub>2</sub>. Hutchins et al. (2007) measured <sup>14</sup>C incorporation over 24 h, an approach comparable to POC production rates in our study, and observed a 40% to 50% increase in carbon fixation when elevating the pCO<sub>2</sub> from 380 to 750  $\mu\text{atm pCO}_2$ . Such responses in growth or POC production rates to elevated pCO<sub>2</sub> exceed those reported for other important marine phytoplankton groups such as diatoms and coccolithophores (Burkhardt et al., 1999; Zondervan et al., 2002; Langer et al., 2006) and demonstrate the exceptionally high sensitivity of *Trichodesmium* to pCO<sub>2</sub>.

The strong responses in growth and POC and PON production rates corroborate previous publications stating that in *Trichodesmium*, central physiological processes must be pCO<sub>2</sub> sensitive. While processes like CCMs and carbon fixation are intrinsically CO<sub>2</sub> dependent (Giordano et al., 2005), a direct CO<sub>2</sub> effect on processes like N<sub>2</sub> fixation appeared unlikely. Furthermore, the observation that the pCO<sub>2</sub> sensitivity of POC and PON production rates is altered by light levels hints at an essential role of energy availability and allocation that we subsequently explored by measuring metabolic processes like N<sub>2</sub> fixation, gross photosynthetic O<sub>2</sub> evolution, CCM activity, as well as the Mehler reaction. Our complementary study focuses on these processes by measuring the respective protein pools (Levitan et al., 2010b).

## N<sub>2</sub> Fixation

Since *Trichodesmium* cultures were grown in artificial medium without nitrogen sources and thus had to acquire all nitrogen for growth by fixation of dissolved

N<sub>2</sub>, the differences in PON production between treatments must be attributed to the respective changes in N<sub>2</sub> fixation. Under both low-light acclimations, N<sub>2</sub> fixation peaked about 3 h after onset of the light and showed reduced activities over midday until the end of the photoperiod (Fig. 2A). This atypical diurnal pattern may be caused by an energy shortage imposed by the low light levels, which first and foremost affect energy-demanding processes such as N<sub>2</sub> fixation. Despite energy shortage under low light, elevated pCO<sub>2</sub> highly stimulated N<sub>2</sub> fixation rates, which implies that more energy is available for this process. Under high light, maximum rates of N<sub>2</sub> fixation rates were more than 6-fold higher than in the low-light acclimations (Fig. 2A) and peaked during midday (5 h after onset of the light), as typically reported for *Trichodesmium* (Berman-Frank et al., 2001). While under low pCO<sub>2</sub>, N<sub>2</sub> fixation rates declined after the midday peak, high pCO<sub>2</sub> levels resulted in a prolonged N<sub>2</sub> fixation until the end of the photoperiod. Such combined effects by light and pCO<sub>2</sub> on the diurnal patterns have not previously been reported and may indicate extended resource and energy availability for N<sub>2</sub> fixation and a



**Figure 4.** HCO<sub>3</sub><sup>-</sup>:CO<sub>2</sub> uptake ratio in *Trichodesmium* IMS101 obtained from HCO<sub>3</sub><sup>-</sup> and gross CO<sub>2</sub> uptake rates (Table III) measured between 2 to 3 h (AM; plain bars) and 6 to 7 h (PM; striped bars) after the beginning of the photoperiod. Error bars indicate 1 SD ( $n \geq 3$ ).

**Table IV.** Leakage ( $CO_2$  efflux: gross carbon uptake) under respective culture conditions for *Trichodesmium* IMS101

Values for two different approaches for leakage estimation are presented. Errors are  $\pm 1$  sd ( $n > 3$ ).

Approach	Acclimation			
	Low Light (50 $\mu\text{mol Photons m}^{-2} \text{s}^{-1}$ )		High Light (200 $\mu\text{mol Photons m}^{-2} \text{s}^{-1}$ )	
	150 $\mu\text{atm pCO}_2$	900 $\mu\text{atm pCO}_2$	150 $\mu\text{atm pCO}_2$	900 $\mu\text{atm pCO}_2$
MIMS-based leakage	0.24 $\pm$ 0.13	0.29 $\pm$ 0.19	0.41 $\pm$ 0.09	0.31 $\pm$ 0.14
$^{13}\text{C}$ -based leakage	0.84 $\pm$ 0.03	0.92 $\pm$ 0.04	0.57 $\pm$ 0.02	0.90 $\pm$ 0.01

change in the regulation of nitrogenase (Levitan et al., 2010b).

As a consequence of the changes in rates and patterns of  $N_2$  fixation under high light and elevated  $pCO_2$ , integrated  $N_2$  fixation rates over the day increased by 200% under low light and 112% under high light (Fig. 2B).  $N_2$  fixation by nitrogenase should be coupled to PON production (Fig. 1C), since  $N_2$  is the only nitrogen source available. While both approaches indeed confirm the strong  $pCO_2$  sensitivity in *Trichodesmium*, the relative stimulation by elevated  $pCO_2$  was larger for the integrated  $N_2$  fixation rates than those of the daily PON production (Figs. 1C and 2B). This apparent difference between acetylene reduction assay (i.e. gross  $N_2$  fixation) and PON production (i.e. net  $N_2$  fixation) could be explained by the loss of previously reduced  $N_2$  as dissolved organic nitrogen (Capone et al., 1994; Glibert and Bronk, 1994) or ammonia (Mulholland et al., 2004) to the medium. In our experimental setup with continuous gas exchange, a significant proportion of ammonia may in fact be stripped out and subsequently cannot be used for PON production.

Fixation of  $N_2$  and PON production differ in their demand for energy and resources. Consequently,  $pCO_2$ -dependent changes in the availability of energy and resources may affect both processes differently. While  $N_2$  fixation by nitrogenase is mainly controlled by the availability of energy and electrons provided by the photosynthetic and respiratory pathways (a minimum of 16 ATP, eight electrons, and eight protons are required to reduce  $N_2$  to  $NH_4^+$ ), the PON accumulation is regulated by glutamine synthetase (GS) and glutamine oxoglutarate aminotransferase (GOGAT), called the GS/GOGAT pathway. The primary substrates for the GS/GOGAT pathway are  $NH_4^+$  and  $\alpha$ -ketoglutarate, a respiratory intermediate of the citric acid cycle, and this pathway requires relatively little energy (one ATP, one NADPH +  $H^+$ , and two protons to form one Glu). For a mechanistic understanding of these findings, it is important to look at possible regulations of key proteins in nitrogen metabolism (Levitan et al., 2010b).

What is the source of the additional energy and resources supporting the observed stimulation in  $N_2$  fixation and PON production under elevated  $pCO_2$ ? To answer this question, we compared the changes of energy generated in photosynthesis and energy consumed by processes involved in carbon metabolism.

## Gross Photosynthesis

Photosynthesis generates energy and reductants that maintain metabolic processes such as  $N_2$  fixation, carbon assimilation, and biomass buildup in *Trichodesmium*. In this study, direct measurements of gross photosynthesis ( $O_2$  evolution from water splitting) yielded rates of photosynthetic electron generation, providing estimations about energy and reductant production. Regardless of  $pCO_2$ , gross photosynthesis was greatly stimulated by light (Fig. 3A). Thus, the enhanced  $N_2$  fixation and PON production rates under high light (Figs. 1 and 2) can be explained by a higher supply of energy and reductants. Gross photosynthesis was insensitive to the applied  $pCO_2$  levels (Fig. 3A). This is comparable with results obtained by Levitan et al. (2007), reporting no change in  $O_2$  evolution for three different  $pCO_2$  acclimations. The production of energy and reductants is not only set by electron generation at PSII but strongly controlled by the downstream processes along the electron transport chain. For example, rapid cyclic electron transport around PSI would yield higher ATP production at the expense of NADPH. We examined these light/ $pCO_2$  effects in more detail at the level of the core proteins of PSII and PSI (Levitan et al., 2010b). Our findings show that elevated  $pCO_2$  did not alter the supply of energy provided by gross photosynthesis. Thus, energy-demanding processes related to carbon metabolism must have been down-regulated to explain the strong stimulation in nitrogen metabolism under elevated  $pCO_2$ .

## Inorganic Carbon Acquisition

Active acquisition of inorganic carbon is a mandatory process for the subsequent carbon fixation in the Calvin-Benson cycle. For the operation of these so-called CCMs, cyanobacteria like *Trichodesmium* need to invest a large amount of energy, which is primarily required due to the poor  $CO_2$  affinity of Rubisco (Badger et al., 1998). *Trichodesmium* IMS101 operates an active CCM based predominantly on the uptake of  $HCO_3^-$  (Kranz et al., 2009). The relative  $HCO_3^-$  contribution to the total carbon fixation was about 90% and remained rather constant under all applied  $pCO_2$  concentrations (150–1,000  $\mu\text{atm}$ ; Kranz et al., 2009). In this study,  $HCO_3^-$  was also the preferred carbon species in all treatments (Fig. 4; Table III). These results

concur with studies showing that CCMs in marine cyanobacteria are generally based on the transport and accumulation of HCO<sub>3</sub><sup>-</sup> within the cell (Price et al., 2008). In some cyanobacteria, internal pools of inorganic carbon were up to 1,000-fold higher than ambient concentrations (Kaplan et al., 1980), emphasizing the generally high energetic costs of their CCMs.

Despite the predominance of HCO<sub>3</sub><sup>-</sup> transport, gross CO<sub>2</sub> uptake rate increased under elevated pCO<sub>2</sub> (Fig. 4; Table III). Genome analysis identified the NAD(P)H dehydrogenase complex (NDH1<sub>4</sub>), a CO<sub>2</sub> uptake system located at the thylakoid membrane (Ohkawa et al., 2001), to be present in *Trichodesmium*. This complex is considered to catalyze the conversion from CO<sub>2</sub> to HCO<sub>3</sub><sup>-</sup> (Badger et al., 2006) by utilizing reductants or electrons provided mostly by electron transport (Friedrich and Scheide, 2000; Price et al., 2002, 2008) and may generate extra ATP by shuffling protons through the Q cycle of the thylakoid membrane (Friedrich and Scheide, 2000; Price et al., 2002). HCO<sub>3</sub><sup>-</sup> uptake, on the other hand, is mediated by BicA transporters that are located in the plasma membrane and function as Na<sup>+</sup>/HCO<sub>3</sub><sup>-</sup> symporters (Price et al., 2004), which are indirectly energized by ATP hydrolysis. Consequently, the changes in HCO<sub>3</sub><sup>-</sup> and CO<sub>2</sub> uptake observed in our study (Fig. 4) may reflect changes in the activity of the CCM components and the availability and/or utilization of ATP, NADPH, or reduced ferredoxin. Furthermore, the changes in uptake ratios may indicate a shift between linear and cyclic electron transport (Li and Calvin, 1998).

The energetic costs associated with the operation of a CCM (Raven and Lucas, 1985) play a central role in the overall energy budget of the cell. Kranz et al. (2009) observed a high plasticity of CCM regulation, for instance in DIC affinities, in response to changes in pCO<sub>2</sub> concentrations and over the photoperiod. Regulation of DIC affinities will likely alter the energy allocation between the CCM and other metabolic processes. The ability of *Trichodesmium* to down-regulate its DIC affinities under elevated pCO<sub>2</sub> (Kranz et al., 2009) and the observed up-regulation in the CO<sub>2</sub> uptake system (Fig. 4; Table III), therefore, could provide parts of the energetic "surplus" to explain the stimulation in nitrogen metabolism and/or organic carbon production.

Although the POC production rates increased significantly under elevated pCO<sub>2</sub> (Fig. 1B), rates of net carbon fixation in the MIMS assays were not stimulated in the high-pCO<sub>2</sub> treatment (Table III). Part of this apparent contradiction may result from the fact that POC production rates cover several generations, including dark and light phases, while net carbon fixation is based on "instantaneous" measurements at specific time points during the photoperiod. Such discrepancies between direct measurements of carbon fixation and daily POC turnover rates in *Trichodesmium* species were also reported for field populations (Mulholland et al., 2006). As *Trichodesmium* IMS101 was able to saturate carbon fixation in

the assays at pCO<sub>2</sub> concentrations of the respective acclimations (data not shown; Kranz et al., 2009), we conclude that the observed changes in POC production cannot be caused by direct effects on the carboxylation efficiency of Rubisco but rather are due to changes in energy availability for downstream processes. Additional information on Rubisco quantities, energy requirements, and availability are provided by Levitan et al. (2010b).

### Leakage and Internal Inorganic Carbon Cycling

In addition to the processes involved in inorganic carbon uptake and accumulation, the ability to reach high rates of carbon fixation also depends on the loss of inorganic carbon via leakage (CO<sub>2</sub> efflux: gross carbon uptake). MIMS-based estimates of leakage ranged between 0.24 and 0.41 in this study (Table IV), confirming values published previously for *Trichodesmium* (Kranz et al., 2009). Similar leakage estimates have been determined for other species of phytoplankton (Rost et al., 2006b; Trimborn et al., 2008), and such values seem reasonable for operating a cost-efficient CCM (Raven and Lucas, 1985). The leakage estimates obtained by <sup>13</sup>C fractionation, on the other hand, were found to be as high as 0.9 (Table IV), a value that would question the benefits of a CCM. It should be noted, however, that <sup>13</sup>C-based leakage estimates are dependent on several assumptions (e.g. the intrinsic fractionation of Rubisco). Also, this approach considers fluxes over the plasma membrane only. However, any kind of internal inorganic carbon cycling would increase <sup>13</sup>C fractionation as the accumulation of <sup>13</sup>CO<sub>2</sub> at the site of carboxylation is lowered (Schulz et al., 2007). Following Sharkey and Berry (1985), high <sup>13</sup>C fractionation values caused by internal inorganic carbon cycling would then be misinterpreted as high leakage over the plasma membrane. Thus, the large differences between MIMS- and <sup>13</sup>C-based leakage estimates in our study likely reflect significant internal inorganic carbon cycling for *Trichodesmium*. High inorganic carbon cycling has also been indicated for other cyanobacteria based on exchange of <sup>18</sup>O from doubly labeled CO<sub>2</sub> in the light (Price et al., 2002, and refs. therein).

The NDH CO<sub>2</sub> uptake systems in cyanobacteria may be involved in both uptake of CO<sub>2</sub> and inorganic carbon cycling as a leakage prevention mechanism (Maeda et al., 2002; Price et al., 2002, 2008). The overestimation of <sup>13</sup>C-based leakage found in the high-pCO<sub>2</sub> treatments (Table IV) may thus reflect higher internal inorganic carbon cycling mediated by the NDH1<sub>4</sub> in *Trichodesmium*. Such inorganic carbon cycling appears consistent with the higher PSI-to-PSII ratio at elevated pCO<sub>2</sub> (Levitan et al., 2010b). An increasing role of NDH1<sub>4</sub> is also indicated by the higher gross CO<sub>2</sub> uptake rates under these conditions (Table III). As a consequence of higher inorganic carbon cycling, more ATP may be produced under elevated pCO<sub>2</sub> (Price et al., 2002), which in turn could

fuel the observed higher N<sub>2</sub> fixation (Fig. 2B). In the low-pCO<sub>2</sub> and high-light acclimation, the relatively small differences in leakage estimates indicate rather low internal inorganic carbon cycling (Table IV). This finding may be attributed to light-dependent O<sub>2</sub> uptake, which was observed only for this treatment (Fig. 3B; see "Discussion" below). Fluorescence data shown by Levitan et al. (2010b) also indicate low cyclic electron transport. However, further investigations on the dynamics of leakage and possible regulations by NDH1<sub>4</sub> in *Trichodesmium* have to be conducted to understand this essential process within its CCM.

### Light-Dependent O<sub>2</sub> Uptake

Processes that reduce the O<sub>2</sub> concentration within the cell may play an important function in supporting and protecting nitrogenase in *Trichodesmium* from oxidative degradation (Kana, 1993; Berman-Frank et al., 2001; Milligan et al., 2007). In particular, the photoreduction of O<sub>2</sub> by the Mehler reaction catalyzes the conversion of O<sub>2</sub> to water. Changes in this O<sub>2</sub>-scavenging process, therefore, could influence N<sub>2</sub> fixation rates. The Mehler reaction was also identified to be involved in photoprotection in other photoautotrophic species (Osmond and Grace, 1995; Osmond et al., 1997; Asada, 1999; Foyer and Noctor, 2000). To test for the presence and role of the Mehler reaction in our different acclimations, light-dependent O<sub>2</sub> uptake was measured.

In low-light-acclimated cells, in situ rates of O<sub>2</sub> uptake in the light were similar to the rates measured in the dark (Fig. 3B; Table II). Irrespective of the light treatment, the O<sub>2</sub> uptake rates were unaffected by the inhibition of PSII activity using 3-(3,4-dichlorophenyl)-1,1-dimethylurea (data not shown). Both observations indicate that the Mehler reaction was not present in *Trichodesmium* IMS101 grown under low light, regardless of pCO<sub>2</sub>. Moreover, they indicate that the respiratory O<sub>2</sub> uptake via the terminal oxidase is not repressed during illumination. These findings provide an additional perspective to the current understanding of the Mehler reaction and the terminal oxidase activity in *Trichodesmium* (Milligan et al., 2007). It is likely that under the low light levels applied here, the Mehler reaction may not be beneficial, as it competes for the "scarce" electrons and its operation would decrease the energy supply for carbon and nitrogen fixation. In addition, the need for O<sub>2</sub> scavenging under low light is reduced because of low photosynthetic O<sub>2</sub> production relative to respiratory O<sub>2</sub> uptake (Table II).

In high-light-acclimated cells, the Mehler reaction was only detected under low pCO<sub>2</sub>. Gross CO<sub>2</sub> uptake (i.e. NDH1<sub>4</sub> activity), inorganic carbon cycling, as well as nitrogenase activity were lower in this treatment than under high pCO<sub>2</sub>. As these processes can use electrons supplied by ferredoxin, lower activities may enhance the proportion of reduced ferredoxin and impede electron transport. Under these conditions, the Mehler reaction could act as a shunt for routing excess

electrons to avoid an overreduction and damage of PSII. Under elevated pCO<sub>2</sub>, where the Mehler reaction was not observed, rates of gross CO<sub>2</sub> uptake, N<sub>2</sub> fixation, as well as POC and PON production may provide sufficient electron sinks, thereby reducing the need for the Mehler reaction.

Short-term exposure of the cells acclimated to 50 μmol photons m<sup>-2</sup> s<sup>-1</sup> to 200 μmol photons m<sup>-2</sup> s<sup>-1</sup> (6 min) resulted in a strong increase in light-dependent O<sub>2</sub> uptake, irrespective of the applied pCO<sub>2</sub> levels (Table II). The apparent operation of the Mehler reaction under these conditions may reduce the sudden electron flux within the electron transport chain, which otherwise may cause photodamage. Furthermore, the Mehler reaction may compensate for some of the light-stimulated O<sub>2</sub> evolution and thus act as a protection mechanism for nitrogenase. Such a relationship between the Mehler reaction and N<sub>2</sub> fixation was observed for *Trichodesmium* in several studies (Kana, 1993; Milligan et al., 2007). However, different growth conditions and the use of significantly higher light levels during these experiments (Kana, 1993; Milligan et al., 2007) could also account for the detection of the Mehler reaction in previous studies.

Under the conditions applied in this study, the Mehler reaction does not contribute to the observed stimulation in N<sub>2</sub> fixation under elevated pCO<sub>2</sub>. Our findings suggest that under our experimental conditions, the Mehler reaction in *Trichodesmium* is involved in photoprotection rather than in O<sub>2</sub> scavenging. This proposed role may be advantageous in view of the high and variable light levels typical for the natural environments of *Trichodesmium* (La Roche and Breitbarth, 2005).

### CONCLUSION

Our data on production rates and elemental composition bear important implications for future changes in the relevant biogeochemical cycles. The pCO<sub>2</sub>-dependent stimulation in the rate of biomass production may increase the CO<sub>2</sub> drawdown in the upper mixed layer and affect the vertical transport of organic matter. This "fertilization" effect on *Trichodesmium* may also expand to other phytoplankton, as this important diazotroph fixes N<sub>2</sub> into particulate and dissolved compounds, thus providing a major source of bioavailable nitrogen to oligotrophic oceans

**Table V.** Parameters of the seawater carbonate system

Values were calculated from TA, pH, phosphate, temperature, and salinity using the CO2Sys program (Lewis and Wallace, 1998). Errors are ±1 SD (*n* > 3).

pCO <sub>2</sub>	CO <sub>2</sub>	TA	pH	DIC
μatm	μmol kg <sup>-1</sup>	μmol kg <sup>-1</sup>	NBS	μmol kg <sup>-1</sup>
150	3.8 ± 0.3	2,487 ± 9	8.57 ± 0.03	1,841 ± 19
900	23.3 ± 1.5	2,470 ± 14	7.94 ± 0.03	2,240 ± 18

(Capone et al., 2005). In addition to the rate of production, biomass buildup is ultimately limited by the availability of other nutrients such as phosphorus. Consequently, the observed increase in carbon to phosphorus and/or nitrogen to phosphorus under elevated pCO<sub>2</sub> may imply that more biomass can be produced per available phosphorus, for instance over the course of a *Trichodesmium* bloom. In terms of the light-dependent changes in CO<sub>2</sub> sensitivity, the rise in pCO<sub>2</sub> may have a stronger effect on *Trichodesmium* thriving in deeper waters than for cells close to the surface. Furthermore, new information about metabolic key pathways and related proteins involved in carbon and nitrogen metabolism are provided in this and the complementary study (Levitan et al., 2010b). Although *Trichodesmium* can saturate carbon fixation even at low pCO<sub>2</sub> levels by operating an efficient CCM, this comes at an energetic cost and competes with other energy-demanding processes like N<sub>2</sub> fixation and the operation of the Calvin cycle. The observed responses to elevated pCO<sub>2</sub> could not be attributed to enhanced energy generation via gross photosynthesis. Instead, energetic costs of the CCM were reduced under high pCO<sub>2</sub>, providing a surplus of energy and reductants that in turn enabled higher rates of N<sub>2</sub> fixation and PON and POC production and growth. Future studies should investigate whether phosphorus and iron limitation, often prevailing in oligotrophic waters, may modify the described effects of this study.

## MATERIALS AND METHODS

### Culture Conditions

Cultures of *Trichodesmium erythraeum* (strain IMS101; originally isolated by Profert-Bebout et al., 1993) were grown at 25°C in 0.2-μm-filtered unbuffered nitrogen-free artificial seawater (YBCII medium; Chen et al., 1996). All cells were cultured as single filaments, grown in 1-L cylindrical glass flasks (diameter of 7 cm), and incubated in a light:dark cycle (12:12 h) with light provided by white fluorescent bulbs (Osram; BIOLUX) at two different light intensities (50 and 200 μmol photons m<sup>-2</sup> s<sup>-1</sup>), representing light-limiting and light-saturating values for *Trichodesmium* according to Breitbarth et al. (2008). Cultures were continuously bubbled with air containing different pCO<sub>2</sub> values of 150 and 900 μatm. The bubbling was sufficient to avoid aggregate formation but did not alter the integrity of the filaments. CO<sub>2</sub> gas mixtures were generated with gas-mixing pumps (Digamix 5KA18/8-F and 5KA36/8-F; Woesthoff) using CO<sub>2</sub>-free air (Nitrox CO<sub>2</sub>RP280; Dornick Hunter) and pure CO<sub>2</sub> (Air Liquide Deutschland). Dilute batch cultivation (i.e. regular dilution with fresh, pre-equilibrated medium) ensured that the carbonate chemistry remained constant and cells stayed in the midexponential growth phase. Cultures in which the pH shifted (pH shift > 0.06) in comparison with a reference (i.e. cell-free medium at the respective pCO<sub>2</sub> levels) were excluded from further analysis.

### Seawater Carbonate Chemistry

Samples for total alkalinity (TA) were taken from the culture filtrate (Whatman GFF filter; approximately 0.6 μm), stored in 100-mL borosilicate bottles at room temperature, and measured by potentiometric titration (Brewer et al., 1981) with an average precision of ±10 μmol kg<sup>-1</sup>. TA was calculated from linear Gran Plots (Gran, 1952). TA measurements were calibrated with certified reference material (Dr. Andrew Dickson, Scripps Institution of Oceanography). The pH<sub>NBS</sub> was determined every morning

using a pH/ion meter (model 713 pH meter; Metrohm). The carbonate system was calculated from TA, pH<sub>NBS</sub>, temperature, salinity, and phosphate using CO2Sys (Lewis and Wallace, 1998). Equilibrium constants of Mehrbach et al. (1973) refitted by Dickson and Millero (1987) were chosen. Carbonate chemistry for the respective pCO<sub>2</sub> treatments are given in Table V.

### Elemental Composition, and Growth and Production Rates

Cells were acclimated to the respective pCO<sub>2</sub> and light levels for at least 30 d (more than 10 generations) prior to harvesting. In all acclimations, samples for growth responses were taken simultaneously at the beginning of the photoperiod to account for diurnal changes. Cell densities were determined using an inverted microscope (Zeiss Axiovert 200) by measuring the number and the length of filaments as well as the cell size in a Sedgwick-Rafter Cell (S50; Graticules).

Samples for POC, PON, and PP were filtered onto precombusted (500°C, 9 h) glass fiber filters (GF/F) and stored in precombusted (500°C, 9 h) petri dishes at -20°C. Prior to analysis, filters for POC were treated with 200 μL of HCl (0.1 N) to remove all inorganic carbon. POC and PON filters were measured in duplicate with a mass spectrometer (ANCA-SL 2020), with an average precision of ±1 μg of carbon and ±0.5 μg of nitrogen, respectively. PP was measured photometrically using a modified version of the ALOHA protocol (Hawaii Institute of Marine Biology, Analytical Services Laboratory at the University of Hawaii).

Growth and POC and PON production rates were determined based on changes in cell density, chl *a*, as well as POC and PON. Growth rates (μ) were calculated according to the following equation:

$$\mu [d^{-1}] = \frac{\ln(N_1) - \ln(N_0)}{\Delta t}$$

where  $N_0$  and  $N_1$  are concentrations (cell, chl *a*, POC, PON) at the beginning ( $t_0$ ) and the end ( $t_1$ ) of sampling, and  $\Delta t$  is the time between sampling intervals. Production rates of POC and PON were calculated according to the following equations:

$$\text{POC production} = \mu \times \text{POC cell}^{-1}$$

$$\text{PON production} = \mu \times \text{PON cell}^{-1}$$

Samples for chl *a* were filtered on GF/filters and immediately stored at -80°C. Chl *a* was subsequently extracted in 5 to 10 mL of 90% acetone (overnight in darkness at 4°C) and determined with a fluorometer (Turner Designs) by measuring nonacidified and acidified fluorescence.

### N<sub>2</sub> Fixation

Rates of N<sub>2</sub> fixation were estimated using the acetylene reduction assay (Capone, 1993). The samples (concentrations between 0.02 and 0.08 μg chl *a* mL<sup>-1</sup>) were spiked with acetylene (20% of head space volume) and incubated for 1 h at acclimation light and temperature with gentle continuous shaking of the bottles to avoid aggregation or settlement. The rate of acetylene reduction to ethylene was measured using a gas chromatograph with a flame-ionization detector (Thermo Finnigan Trace) and quantified relative to an ethylene standard. Rates were normalized to chl *a*, and a conversion factor of 4:1 (Capone and Montoya, 2001) was applied to convert ethylene production to N<sub>2</sub> fixation rates. To account for the diurnal patterns, nitrogen fixation rates were measured every 2 h from the onset of light until 2 h after dark.

### Photosynthetic O<sub>2</sub> Evolution and O<sub>2</sub> Uptake

Rates of net O<sub>2</sub> production and O<sub>2</sub> uptake were measured by MIMS. All MIMS measurements were carried out in an 8-mL thermostatted cuvette, which was attached to a sectorfield multicollector mass spectrometer (IsoPrime; GV Instruments) via a gas-permeable membrane (PTFE; 0.01 mm) inlet system. O<sub>2</sub>-evolving and O<sub>2</sub>-consuming processes can be separated in the light by measuring <sup>16</sup>O<sub>2</sub> evolution from water splitting and <sup>18</sup>O<sub>2</sub> uptake from the medium. To this end, the medium was initially bubbled with nitrogen to remove all the <sup>16</sup>O<sub>2</sub> and then enriched with <sup>18</sup>O<sub>2</sub>, ensuring that mainly <sup>18</sup>O<sub>2</sub> is taken up by O<sub>2</sub>-consuming processes. For further details on the calculations of

O<sub>2</sub> fluxes, the reader is referred to Peltier and Thibault (1985) and Fock and Sültemeyer (1989).

Assays were performed in YBCII medium buffered with HEPES (50 mM, pH 7.8) or Bicine (50 mM, pH 8.4) depending on the respective pCO<sub>2</sub> of the acclimation. To obtain assay conditions, the medium was purged with N<sub>2</sub> overnight, subsequently sealed in 40-mL glass bottles, and spiked with 20 to 40 μL of <sup>18</sup>O<sub>2</sub> to yield air-equilibrated O<sub>2</sub> concentrations (i.e. 21%). For measurements, cells were concentrated by gentle filtration (8 μm; Isopore; Millipore). The culture medium was exchanged stepwise with the <sup>18</sup>O<sub>2</sub>-enriched assay medium, and cells were subsequently transferred to the MIMS cuvette. Light and dark intervals lasted 6 min to obtain O<sub>2</sub> fluxes under steady-state conditions. DIC concentrations were adjusted by the addition of a 1 M HCO<sub>3</sub><sup>-</sup> solution prior to measurements. Measurements were performed at respective acclimation light (50 or 200 μmol photons m<sup>-2</sup> s<sup>-1</sup>) and DIC (approximately 1,900 or 2,300 μmol of DIC) levels if not mentioned otherwise. Chl *a* concentration during the measurement ranged between 0.4 and 1.6 μg mL<sup>-1</sup>.

## Inorganic Carbon Acquisition and Leakage

Uptake of net photosynthesis, inorganic carbon sources (CO<sub>2</sub> or HCO<sub>3</sub><sup>-</sup>) for photosynthesis, and leakage (CO<sub>2</sub> efflux: gross carbon uptake) were determined by MIMS measurements according to Badger et al. (1994). This approach is based on simultaneous measurements of O<sub>2</sub> and CO<sub>2</sub> during consecutive light and dark intervals at steady-state photosynthesis. For measurements, cells were concentrated in the same manner as for the O<sub>2</sub> flux measurements, exchanging growth medium with assay medium (pH 7.8 and 8.4) containing air-equilibrated O<sub>2</sub> levels. Light and dark intervals during the assay lasted 6 min. Light was adjusted to the respective photon flux densities in the acclimation (50 or 200 μmol photons m<sup>-2</sup> s<sup>-1</sup>). To completely inhibit external carbonic anhydrase activity, dextran-bound sulfonamide was added to a final concentration of 50 μmol L<sup>-1</sup>. Chl *a* concentrations during the measurement ranged between 0.5 and 2 μg mL<sup>-1</sup>. Further details on the method and calculations are given by Badger et al. (1994) and Rost et al. (2007).

To obtain additional information about leakage, isotopic composition of POC (δ<sup>13</sup>C<sub>POC</sub>) was determined by EA-mass spectrometry (ANCA-SL 2020) following Rost et al. (2006a). Isotopic fractionation during POC formation (ε<sub>p</sub>) was calculated relative to the isotopic composition of CO<sub>2</sub> (δ<sup>13</sup>C<sub>CO2</sub>) in the medium. To determine the isotopic composition of DIC (δ<sup>13</sup>C<sub>DIC</sub>), 8 mL of the culture medium was fixed with HgCl<sub>2</sub> (approximately 110 mg L<sup>-1</sup> final concentration). Extractions and measurements were performed in the laboratory of H.J. Spero (University of California, Davis) with a precision of ±0.11‰. The isotopic composition of CO<sub>2</sub> (δ<sup>13</sup>C<sub>CO2</sub>) was calculated from δ<sup>13</sup>C<sub>DIC</sub> following a mass-balance equation (Zeebe and Wolf-Gladrow, 2007). Isotopic fractionation is driven by the intrinsic discrimination of <sup>13</sup>C by Rubisco (ε<sub>i</sub>), setting the upper-most values for ε<sub>p</sub>. Variations in fractionation are principally determined by changes in leakage as well as carbon source taken up (Sharkey and Berry, 1985):

$$\varepsilon_p = a \times \varepsilon_s + L \times \varepsilon_t$$

where ε<sub>i</sub> is assumed to be approximately 25‰ (Guy et al., 1993), ε<sub>s</sub> represents the equilibrium fractionation between CO<sub>2</sub> and HCO<sub>3</sub><sup>-</sup>, and *a* is the fractional contribution of HCO<sub>3</sub><sup>-</sup> to total inorganic carbon uptake. Since HCO<sub>3</sub><sup>-</sup> is about 9‰ enriched in <sup>13</sup>C relative to CO<sub>2</sub> (Zeebe and Wolf-Gladrow, 2007), an increasing proportion of HCO<sub>3</sub><sup>-</sup> uptake reduces the ε<sub>p</sub> value, which is defined relative to CO<sub>2</sub> as the carbon source. If there is no change in carbon source, ε<sub>p</sub> increases with increasing leakage.

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