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ABSTRACT: Dinitrogen (N_2) fixation by prokaryotic microorganisms provides bioavailable nitrogen in oligotrophic marine ecosystems such as coral reefs. The widespread though largely unknown heterotrophic diazotrophs require dissolved organic matter (DOM) for their nutrition. In coral reef ecosystems, DOM-rich mucus released by corals potentially sustains heterotrophic diazotrophic growth and activity. In this study, we investigated the effect of coral mucus on planktonic N_2 fixation in *in situ* experiments over a seasonal cycle within a New Caledonian lagoon, as well as in *in vitro* experiments in which the effect of mucus was monitored for 72 h. During the field experiment, N_2 fixation rates ranged between 0.12 and 7.90 nmol N l^{-1} d^{-1}. Despite the highest N_2 fixation being found after mucus release, no significant difference was measured between the seawater surrounding the coral before and after mucus release. Similarly, the addition of mucus during the *in vitro* experiment enhanced N_2 fixation rates 1.5-fold, but this increase was not significantly different from the control. The abundance of 2 dominant populations of diazotrophs associated with corals and their surrounding seawater environments (unicellular cyanobacteria and rhizobia) found within pure mucus samples was on average 18-fold higher than in the surrounding seawater in the summer period and 400-fold higher in the winter. Our results suggest that although coral mucus does not influence planktonic N_2 fixation, the release of large numbers of diazotrophic cells associated with the mucus likely influences the abundance and diversity of diazotroph populations within the lagoon waters.

KEY WORDS: Diazotrophs · Coral mucus · Dissolved organic matter · Pelagic–benthic interactions

INTRODUCTION

Coral reefs are among the most productive and diverse ecosystems on the planet (Sorokin 1993), despite their location in generally oligotrophic waters with low concentrations of nutrients such as bioavailable nitrogen (Furnas 1992). Nitrogen limitation in coral reefs is notably counteracted by dinitrogen (N_2) fixation (Wiebe et al. 1975), which takes place in a variety of reef compartments, including the substrata (Wilkinson et al. 1984), algal turfs (Den Haan et al. 2014, Rix et al. 2015), microbial mats and seagrass meadows (Charpy et al. 2012, Cardini et al. 2014), coral skeletons (Larkum 1988, Davey et al. 2008), endosymbionts of hard and soft corals (Shashar et al. 1994, Lesser et al. 2004, 2007, Lema et al. 2014, Bednarz et al. 2015, Cardini et al. 2015, Rädecker et al. 2015), as well as in pelagic plankton communities (Biegala & Raimbault 2008, Riemann et al. 2010, Turk-Kubo et al. 2015). Among these sources, primary

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production in coral reef lagoons is likely sustained by benthic diazotrophs and particularly by cyanobacterial mats (Casareto et al. 2008). However planktonic diazotrophs also have a role, with previous work suggesting that their N_2 fixation activity could sustain high levels of planktonic primary production in a New Caledonian lagoon (Garcia et al. 2007).

Autotrophic diazotrophs such as filamentous and unicellular cyanobacteria (UCYN) were long thought to be the sole contributors to pelagic N_2 fixation (Capone et al. 1997, Moisander et al. 2010). However, recent studies have demonstrated that heterotrophic diazotrophs such as the non-photosynthetic UCYN-A, Archaea and other bacterial diazotrophs are more widespread and abundant on a global basis (Farnelid et al. 2011, Luo et al. 2012), and especially active in the South Pacific (Halm et al. 2012, Moisander et al. 2014). Yet, their contribution to global fixed N_2 inputs to the oceans and their ecology remain elusive. Non-autotrophic diazotrophs rely on external dissolved organic matter (DOM) inputs for their nutrition and growth, and therefore to understand their ecology their interactions with *in situ* organic matter pools needs to be investigated (Riemann et al. 2010).

The presence and activity of heterotrophic (i.e. DOM-dependent) diazotrophs in the pelagic compartment of coral reef ecosystems could be sustained by organic substances produced and released by the coral as mucus. Coral mucus is a carbohydrate complex rich in polysaccharides, lipids, triglycerides, proteins and other compounds all of which provide an adequate substrate for bacterial growth (Nakajima et al. 2009, Tanaka et al. 2011). While it is well known that the activity and abundance of heterotrophic planktonic bacteria respond to coral mucus release (e.g. Huettel et al. 2006, Allers et al. 2008), the relationship between coral mucus and planktonic diazotrophs remains unknown. Because heterotrophic diazotrophs are more abundant than autotrophic ones in the world's oceans (Halm et al. 2012, Turk-Kubo et al. 2015), their dependence on DOM and effect on nitrogen dynamics within coral reef ecosystems needs to be elucidated.

The objective of this study was to investigate the relationship between the activity of planktonic diazotrophs and the DOM released by corals into seawater in the form of mucus. With this aim we measured N_2 fixation activity in the waters above and around coral colonies, before and after mucus release within the New Caledonian lagoon and experimentally tested the effect of mucus additions on N_2 fixation *in vitro*. In addition, we quantified 2 groups of diazotrophs present in the seawater column and in pure mucus samples.

MATERIALS AND METHODS

Study area and sample collection

Seawater and coral mucus samples were collected within 2 contrasted reefs in New Caledonia (south-western tropical Pacific): an offshore station (L2) located 17 km off the coast on the barrier reef 'Recif Aboré' (22° 33.87′ S, 166° 28.2′ E), which is an environmentally protected area (Kulbicki et al. 1996); and a coastal station (D39) located near the mouth of the Dumbéa River at Pointe Bovis (22° 18.9′ S, 166° 21.9′ E), which presents less oligotrophic character due to river runoff (Jacquet et al. 2006). The sampling was performed on a monthly basis between February (austral summer) and July (winter) 2014 (see Table 1 below). The depth of the water column during sampling was 5 to 6 m.

At each station seawater was collected into twelve 4.3 l transparent polycarbonate bottles to measure planktonic N_2 fixation and diazotroph abundance. Seawater was collected using an air-compressed Teflon pump (Astii) connected to PVC tubing (1) from the surface (0.5 m depth), (2) from ~6 m above the coral colonies before stressing the corals, and (3) after the corals had been stressed and started releasing mucus. Mucus release was induced by applying mechanical stress with sand as described in Mitchell & Chet (1975). After the sand had settled onto the coral colony (~3 min), predominantly composed of *Acropora* sp. and once corals started releasing mucus, seawater containing mucus strands were collected by scuba divers using polycarbonate bottles as above. An additional set of samples included pure mucus samples, obtained by cutting 5 or 6 *Acropora* sp. branches (10 to 15 cm long), which were gently washed with sterile 0.2 µm-filtered seawater and placed upside down to release the mucus. The mucus released over the first 30 s was discarded to avoid any contamination with coral surface bacterial communities (Naumann et al. 2009). We always used *Acropora* sp. for our experiments, as it is one of the 3 dominant hermatypic coral species in the New Caledonian lagoon (Adjeroud et al. 2010)

Hydrography and nutrient analysis

All seawater samples were collected in acid-washed 20 ml polyethylene vials and preserved with $HgCl_2$ (1% final concentration) for the analysis of nitrate plus nitrite (NO_x) and phosphate (PO_4^{3-}). All samples were kept in the dark at 4°C until analysis.

Table 1. Measured values of core parameters (temperature, salinity) and inorganic nutrient concentrations NO_x (nitrate plus nitrite) and PO_4^{3-} at 1 coastal station (Stn D39) and 1 offshore station (Stn L2) on coral reefs in the New Caledonian lagoon. Seawater samples were measured in surface water (0.5 m depth; Surface), in water above coral colonies (~6 m; Above coral), and water above the colonies after the corals had been stressed and started releasing mucus (~6 m; After stressing). n/a: data not available

Date (in 2014)	Temp. (°C)	Salinity	Sample	NO_x (µmol l^{-1})	PO_4^{3-} (µmol l^{-1})
Stn D39					
17 Feb	27.03	34.54	Surface	0.60	0.04
			Above coral	0.43	0.09
			After stressing	0.57	0.03
03 Apr	26.07	34.85	Surface	0.70	0.04
			Above coral	0.37	0.03
			After stressing	0.40	0.19
30 Apr	25.97	35.06	Surface	0.34	0.02
			Above coral	0.58	0.04
			After stressing	0.49	0.51
21 May	23.34	n/a	Surface	0.51	0.04
			Above coral	0.50	0.04
			After stressing	0.40	0.11
16 Jul	22.15	n/a	Surface	0.07	0.01
			Above coral	0.14	0.00
			After stressing	0.19	0.02
Stn L2					
17 Feb	26.16	35.3	Surface	0.41	0.00
			Above coral	0.62	0.06
			After stressing	0.67	0.07
03 Apr	25.60	35.18	Surface	1.30	0.06
			Above coral	1.36	0.11
			After stressing	1.10	0.09
30 Apr	25.83	35.24	Surface	0.58	0.04
			Above coral	0.60	0.04
			After stressing	0.51	0.69
21 May	22.93	35.66	Surface	0.87	0.14
			Above coral	0.89	0.14
			After stressing	0.93	0.26
16 Jul	22.50	35.62	Surface	0.15	0.04
			Above coral	0.14	0.03
			After stressing	0.13	0.03

Nutrient concentrations were determined according to Kérouel & Aminot (1997) using a Bran+Luebbe III nutrient autoanalyzer. Temperature and salinity were measured using a SBE56 conductivity-temperature-depth (CTD) probe.

N_2 fixation rates

To measure planktonic N_2 fixation rates, seawater sampled before and after mucus release was collected in triplicate (n = 3) and amended with $^{15}N_2$-enriched seawater as described in Großkopf et al. (2012). To prepare the $^{15}N_2$-enriched seawater (from the same site where the corresponding sample was collected), water was filtered through 0.2 µm and degassed for 1 h at a flow rate of 450 ml min^{-1} using a degassing membrane (Membrana, Minimodule) connected to a vacuum pump (<200 mbar). The degassed seawater was transferred into a 4.5 l tedlar bag and 45 ml of $^{15}N_2$ (98.3 atom% $^{15}N_2$, Cambridge Isotope Laboratories) were injected. The bag was then struck with a wooden stick until the $^{15}N_2$ bubble was completely dissolved. $^{15}N_2$-enriched seawater was added to the incubation bottles at 5% vol:vol (i.e. 225 ml), sealed without headspace using silicon septum screw caps. The bottles were incubated for 24 h under *in situ* simulated conditions in an incubator covered with neutral density screening and cooled with circulating water to reproduce irradiance and temperature conditions corresponding to the original sampling depth. Two extra 4.3 l bottles were filled with surface seawater and with the water closer to the corals, spiked with $^{15}N_2$ and immediately filtered to determine the natural $^{15}N_2$ enrichment of the particulate organic N (PON) at time zero (T_0), which is required for calculations of N_2 fixation rates (Montoya et al. 1996).

At the end of the incubation period, the bottles were filtered through pre-combusted (450°C, 5 h) 25 mm GF/F filters (Whatman), stored at −20°C and dried at 60°C for 24 h before analysis. The PON content and its ^{15}N enrichment were measured on an elemental analyzer coupled to an isotope ratio mass spectrometer (EA-IRMS, SERCON Integra CN). N_2 fixation rates were calculated as described in Montoya et al. (1996). Rates were considered significant when the $^{15}N_2$ enrichment of the PON was higher than 3 times the standard deviation obtained from T_0 samples.

Quantification of diazotrophs

UCYN and rhizobia were chosen to quantify diazotroph abundance in our seawater and mucus samples as these 2 groups are abundant in Southwest Pacific coral reef ecosystems (Biegala & Raimbault 2008, Lema et al. 2014). *Trichodesmium* and diatom–diazotroph associations are also abundant in the New Caledonian lagoon (Turk-Kubo et al. 2015) but were not targeted by our TSA-FISH (tyramide signal amplification fluorescent *in situ* hybridization) analyses as our objective was to study the effect of mucus on heterotrophic planktonic diazotrophs, and cyanobacterial

diazotrophs associated to diatoms are autotrophic. To quantify UCYN and rhizobia, the 4.3 l seawater samples were collected in April (summer) and July (winter) at each station under the 3 conditions of sampling described above. The samples were sequentially size-fractionated through 47 mm polycarbonate filters of 10, 3 and 0.2 µm (Millipore). For the 10 and 3 µm size fractions, 3.5 to 4 l and 2 to 2.5 l were filtered by gravity, respectively, while 200 to 500 ml were filtered under low vacuum pressure (200 mm Hg) for the 0.2 µm fraction. To quantify the abundance of UCYN and rhizobia within the mucus, 5 ml of pure mucus were diluted in 100 ml of 0.2 µm-filtered sterile seawater, and then size-fractionated as previously detailed. All filters were fixed with 1% paraformaldehyde at room temperature for 15 min. Subsequently, the cells were dehydrated with 100% ethanol for 10 min and stored at −80°C until analysis.

UCYN and rhizobia cells were quantified using the TSA-FISH method according to Biegala & Raimbault (2008), Bonnet et al. (2009), Ramm et al. (2012) and Agawin et al. (2014) with slight modifications. The cells were permeabilized with lysozyme (5 mg ml^{-1}) at 37°C for 1 h and achromopeptidase (60 U ml^{-1}) at 35°C for 30 min. To reduce the autofluorescence of cells and coral debris, a bath of H_2O_2 at 3% (10 min) was added to the protocol. UCYN and rhizobia were respectively hybridized with probes Nitro821 (5′-CAA GCC ACA CCT AGT TTC-3′) and Rhiz1244 (5′-TCG CTG CCC ACT GTC ACC-3′), both labeled with horseradish peroxidase. The general bacteria probe EU338mix (5′-GCW GCC WCC CGT AGG WGT-3′) was also used as a positive control. All samples were also counterstained with 4,6-diamidino-2-phenylindole (DAPI) (Vectashield). The cells were counted under an epifluorescence microscope (Axioskop 2) equipped with a mercury lamp (HBO 100 W) and dichroic filters of 360 ± 20 excitation, 410 ± 5 emission for DAPI (blue fluorescence) and 480 ± 20 excitation, 535 ± 40 emission for fluorescein (green fluorescence). Due to the low abundance of diazotrophs, the entire surface of each filter portion was counted.

Mucus addition experiment

In addition to the measured N_2 fixation rates in the seawater surrounding coral colonies after being stressed (i.e. mucus released), we also tested the effect of coral mucus on N_2 fixation rates and planktonic community structure by adding 2 ml of pure mucus to 4 sets of triplicate 2.3 l bottles (n = 12) containing seawater from Stn L2. Four further sets (n = 12) of triplicate 2.3 l bottles were also sampled and served as untreated controls. Two sets of triplicates were used as T_0 samples (initial conditions; n = 6), with 1 triplicate used as the control (no mucus addition; n = 3), and 1 triplicate containing mucus (n = 3). Control and treated bottles were incubated for 24, 48 and 72 h (n = 6 each). At T_0 and at each time point, triplicate bottles were subsampled in order to measure the evolution of inorganic nutrient concentrations (NO_x and PO_4^{3-}), N_2 fixation rates and picoplankton abundance (including bacteria, *Prochlorococcus*, *Synechococcus* and picoeukaryotes).

Picoplankton was quantified on 1.8 ml samples fixed with 2% paraformaldehyde (final concentration) using a FACSCalibur flow cytometer (BD Biosciences). For the quantification of bacteria, the samples were stained with SYBR Green I (Invitrogen) at room temperature in the dark for 15 min. Fluorescent microspheres (Trucount and 2 µm beads, BD Biosciences) were added as an internal standard. The samples were run in medium mode for 1 min. Red versus green fluorescence, and green versus side scatter cytograms were used to gate the bacteria using the FlowJo software.

Statistical tests

The effect of the release of mucus on the N_2 fixation rate on the water column and the effect of sampling station were performed with an unpaired *t*-test (N_2 fixation rates were previously log transformed to make them normally distributed). For the mucus addition experiment, an unpaired *t*-test was also used to compare the variation of N_2 fixation rate in time, as well as the picoplankton abundance, between control and treated samples. These comparisons were done for each time point (0 h, 24 h, 48 h and 72 h) of the experimentation. All statistical analyses were performed with the GraphPad Prism 5 (GrapPad Software). Statistical significance was accepted at $p < 0.05$. All mean values measured between replicate sampling were expressed with their standard deviation.

RESULTS

Environmental parameters

Between the sampling period of February and July 2014, seawater temperatures decreased from ~27 to ~22°C at the coastal station D39, and from ~26 to ~23°C at the offshore station L2 (Table 1). Salinity

increased slightly from 34.5 to 35 at Stn D39 between February and April 2014 (data from May and July are not available), while it was stable throughout the whole sampling period at Stn L2 (~35.2 to 35.5) (Table 1).

NO_x concentrations were <1.5 µM and were, in most cases, lower at Stn D39 compared to Stn L2. Vertical differences throughout the water column were not observed (even when seawater included coral mucus), suggesting a high degree of mixing in these shallow waters as previously reported in the New Caledonian lagoon (Ouillon et al. 2010). Conversely, PO_4^{3-} concentrations showed contrasting values between different samples collected throughout the water column and from coral mucus. In most cases, they were higher at Stn D39 than at Stn L2. The PO_4^{3-} content in the seawater containing mucus doubled or tripled in samples from March, April and May, but such differences were not observed in February and July (Table 1).

N_2 fixation rates in field samples

Overall, the lowest rates of N_2 fixation were in surface waters and they were similar at both Stns D39 and L2 (ranging between 0.1 and 0.7 nmol N l^{-1} d^{-1}, Fig. 1) except in early April when a peak of activity was observed at Stn D39 (>2.0 nmol N l^{-1} d^{-1}), being 3.4-fold higher than that measured at Stn L2 (*t*-test, $p < 0.01$). Although N_2 fixation rates found in the waters above coral (i.e. seawater without mucus) were up to 2.7-fold higher than those measured at the surface, no significant differences were observed between them ($p > 0.05$), except in April at Stn D39 ($p < 0.001$), when N_2 rates reached a maximum of 4.6 nmol N l^{-1} d^{-1}.

The highest N_2 fixation rates were measured in seawater samples above the corals after mucus release (ranging between 0.3 and 1.5 nmol N l^{-1} d^{-1}), being similar between the 2 stations. Nevertheless, again in early April, a peak of activity was observed, when N_2 fixation rates were 5.8-fold higher at Stn D39 than at Stn L2 (*t*-test, $p < 0.01$). However, only the N_2 fixation rates measured in February, at the beginning of April and in May ($p < 0.05$) were significantly higher after stressing the corals than those measured at the surface for the coastal station D39 (Fig. 1a). At the offshore station L2, only the rates measured in February for the water after stressing the corals were significantly higher ($p < 0.01$, Fig. 1b) than those measured in the surface water.

N_2 fixation rates found after stressing the corals were not significantly different (*t*-test, $p > 0.05$) than those measured in seawater above the corals not containing mucus except in February ($p < 0.01$) and then only at Stn D39 (Fig. 1a), where the N_2 fixation rates measured after stressing coral (i.e. mucus-affected) were 5.0-fold higher than those not containing mucus.

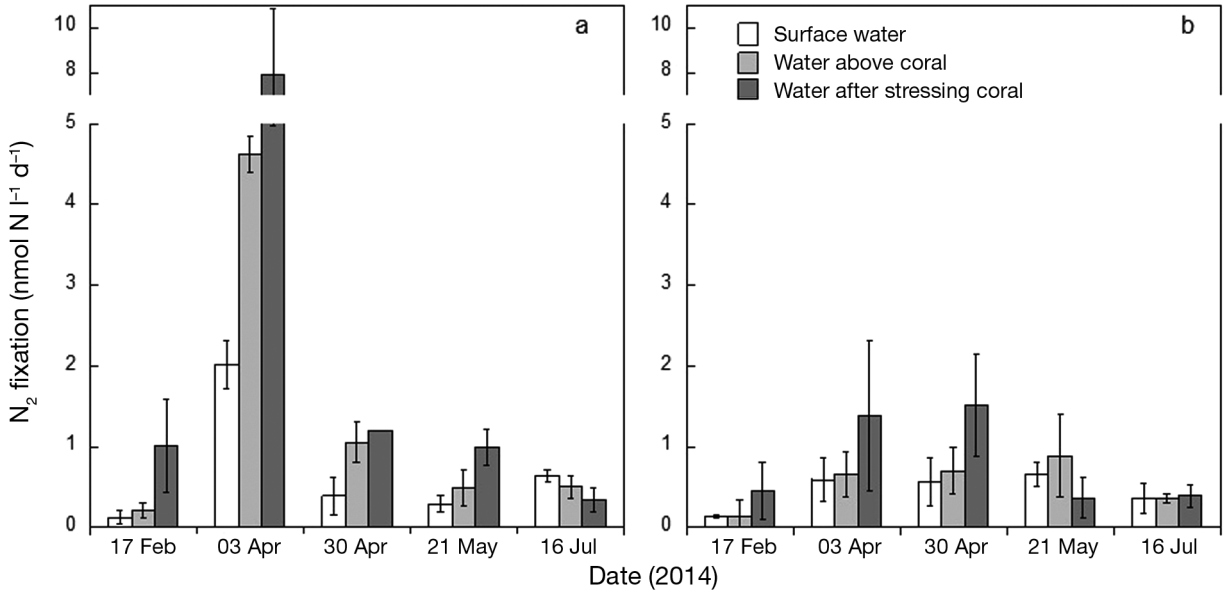

Fig. 1. Coral N_2 fixation rates at stations in the New Caledonian lagoon, measured in surface water (0.5 m depth), water above coral (~6 m), and water above the coral after stressing the corals: (a) coastal station D39; (b) offshore station L2. Error bars represent the standard deviation of the mean

Quantification of diazotrophs

The abundance of UCYN in the water column before and after the release of mucus for the summer (April) and winter (July) periods ranged from 0.5 to 13.9 cells ml^{-1} and was generally higher at Stn D39 than at Stn L2, and in summer as compared to winter (Fig. 2a–f). UCYN were less abundant in surface waters (Fig. 2a,b) compared to waters above corals (Fig. 2c,d), and to waters above corals after stressing the corals, i.e. containing mucus (Fig. 2e,f). In mucus samples, UCYN abundances were on average 286- and 616-fold higher than in the water column at Stns D39 and L2, respectively (Fig. 2g,h), reaching a maximum of 719.8 cells ml^{-1} (Fig. 2g,h). Cells from the picoplanktonic fraction (retained on 0.2 µm filters) dominated over nano- and microplanktonic cells (collected on 3 and 10 µm filters) in all cases (Fig. 2), averaging ~60% of the total UCYN community in summer and >90% in winter.

The abundances of rhizobia in the water column ranged from 1.5 to 125.8 cells ml^{-1} and were ~0.5- to 12-fold higher than those of UCYN. Similarly to UCYN, the rhizobia were more abundant in the summer than in the winter (Fig. 3a–f), but the differences between Stns D39 and L2 were less pronounced than those observed for UCYN. The abundances of rhizobia were similar throughout the water column and were on average 3.5-fold higher after stressing the corals (Fig. 3e,f) than in waters not containing mucus (surface waters and waters above corals collected before mucus release), with greater abundance detected at Stn L2 than at Stn D39. As observed for UCYN, the highest abundance of rhizobia was detected in pure mucus samples at both stations, reaching 526.2 cells ml^{-1}. For both stations the abundance of rhizobia found in the pure mucus was 1.5-fold higher in winter compared to summer.

Mucus addition experiment

Mucus additions to natural seawater during a 72 h incubation period demonstrated varying degrees of enhanced N_2 fixation rates, which ranged from 0.14 ± 0.01 to 4.94 ± 0.93 nmol N l^{-1} d^{-1} for the water amended with coral mucus compared to 0.29 ± 0.05 to 2.76 ± 0.84 nmol N l^{-1} d^{-1} for the controls without mucus addition. Despite the addition of mucus leading to a peak of activity observed at 24 h, it did not result in a significant change with respect to the control (*t*-test, $p > 0.05$) over the 72 h of the experiment. The highest N_2 fixation rates were measured after

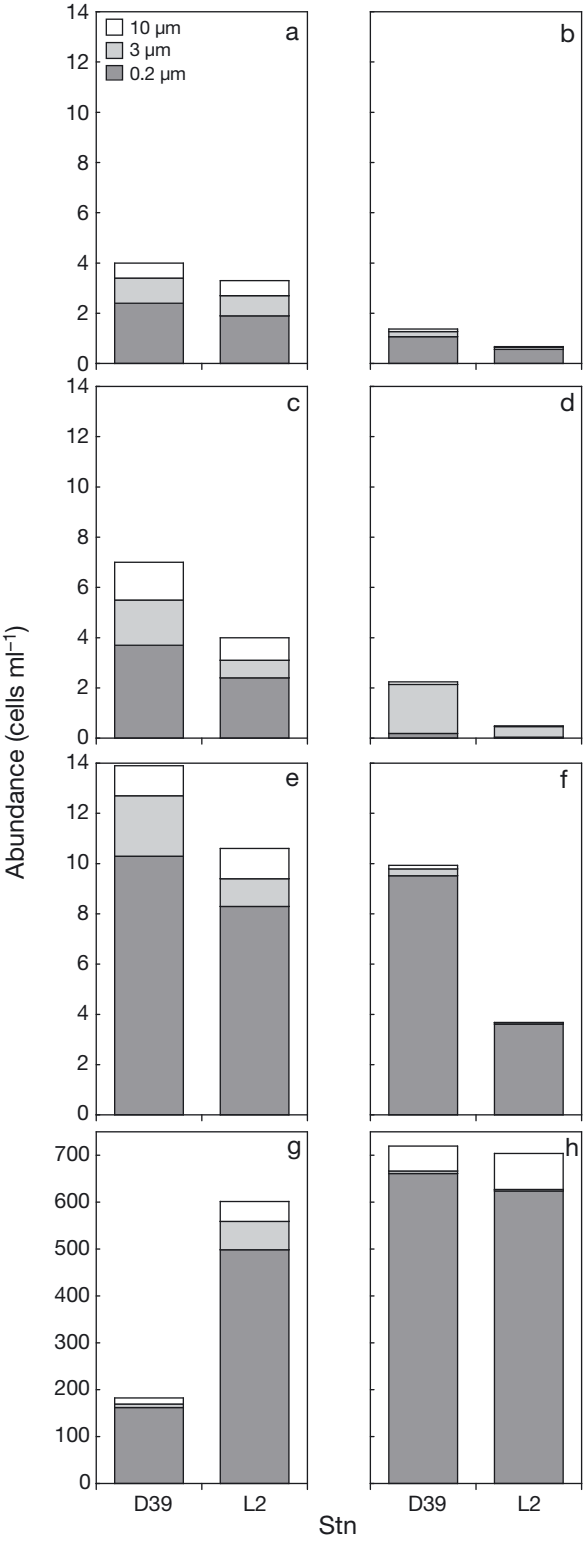

Fig. 2. Relative contribution of the different size fractions (0.2, 3 and 10 µm) to overall Nitro821-positive cells counted with the TSA-FISH technique for Stns D39 and L2 in summer (left panels) and winter (right panels) in (a,b) surface water, (c,d) water above the coral colonies, (e,f) water above the colonies after stressing the corals and (g,h) coral mucus

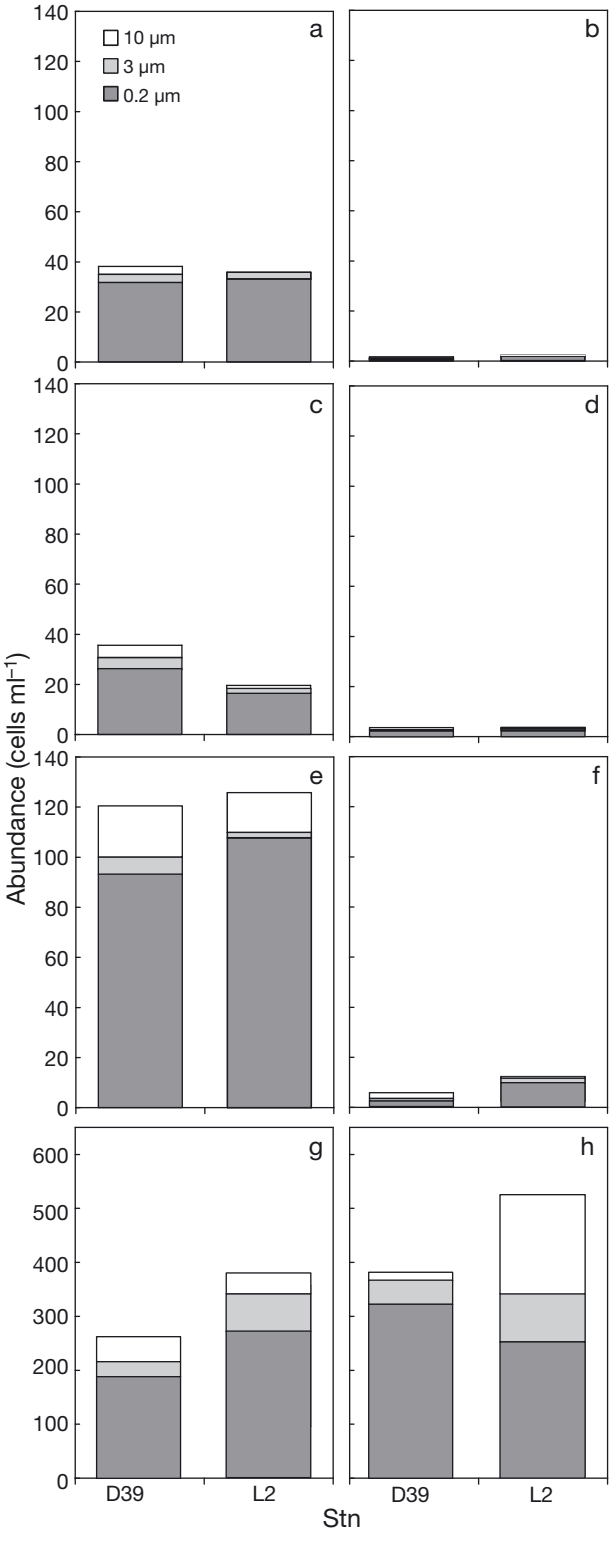

Fig. 3. Relative contribution of the different size fractions (0.2, 3 and 10 µm) to overall Rhizobia-positive cells counted with the TSA-FISH technique for Stns D39 and L2 in summer (left panels) and winter (right panels) in (a,b) surface water, (c,d) water above the coral colonies, (e,f) water above the colonies after stressing the corals and (g,h) coral mucus

24 h (~3 and ~5 nmol N l^{-1} d^{-1} for control and mucus-amended samples, respectively; Fig. 4a); rates then decreased to values close to 1.2 and 1.5 nmol l^{-1} d^{-1} for the control and mucus-amended samples at the 48 and 72 h time points, respectively (Fig. 4a).

NO_x and PO_4^{3-} concentrations decreased over the incubation period, ranging from ~0.6 to 0.3 µM and from ~0.1 to 0.01 µM for NO_x and PO_4^{3-} (Fig. 4b,c). NO_x concentrations measured at 24 h were significantly higher (*t*-test, $p < 0.05$) in the mucus-amended treatments compared to the control, and PO_4^{3-} concentrations were significantly ($p < 0.05$) higher in the mucus-amended treatments at T_0 and after 48 h of incubation. NO_x and PO_4^{3-} concentrations decreased from T_0 to 72 h both for the control and for the mucus-amended treatments.

Bacterial and *Prochlorococcus* abundance increased by 2- to 3-fold at 24 h with respect to T_0 and then decreased towards the end of the incubation (Fig. 4d,e), while the abundance of *Synechococcus* and picoeukaryotes increased progressively over time for the mucus-amended treatments and control (Fig. 4f,g). Bacteria were significantly more abundant in the mucus-amended treatments than in the control samples at T_0, 24 and 48 h ($p < 0.05$). These differences were not significant (*t*-test, $p > 0.05$) for *Prochlorococcus, Synechococcus* and picoeukaryotes.

DISCUSSION

Coral mucus does not enhance planktonic N_2 fixation

Studies have previously shown that bacterial abundance and production in the pelagic compartment is enhanced when coral mucus is released into the seawater or isolated samples are amended with mucus (e.g. Allers et al. 2008, Nakajima et al. 2009, Shnit-Orland & Kushmaro 2009). In this study, we hypothesized that the activity and/or abundance of planktonic heterotrophic diazotrophs could be enhanced by organic matter-rich coral mucus released into the water column. To the best of our knowledge this study is the first to directly test the effect of mucus on pelagic diazotrophy.

Our results indicate that mucus derived from corals can increase the abundance of bacteria within the seawater adjacent to the corals (Fig. 4d) and that it contains a high abundance of diazotrophs (e.g. up to 790-fold higher in winter; Figs. 2 & 3). Although planktonic N_2 fixation rates were higher after mucus was released into the surrounding seawater at the

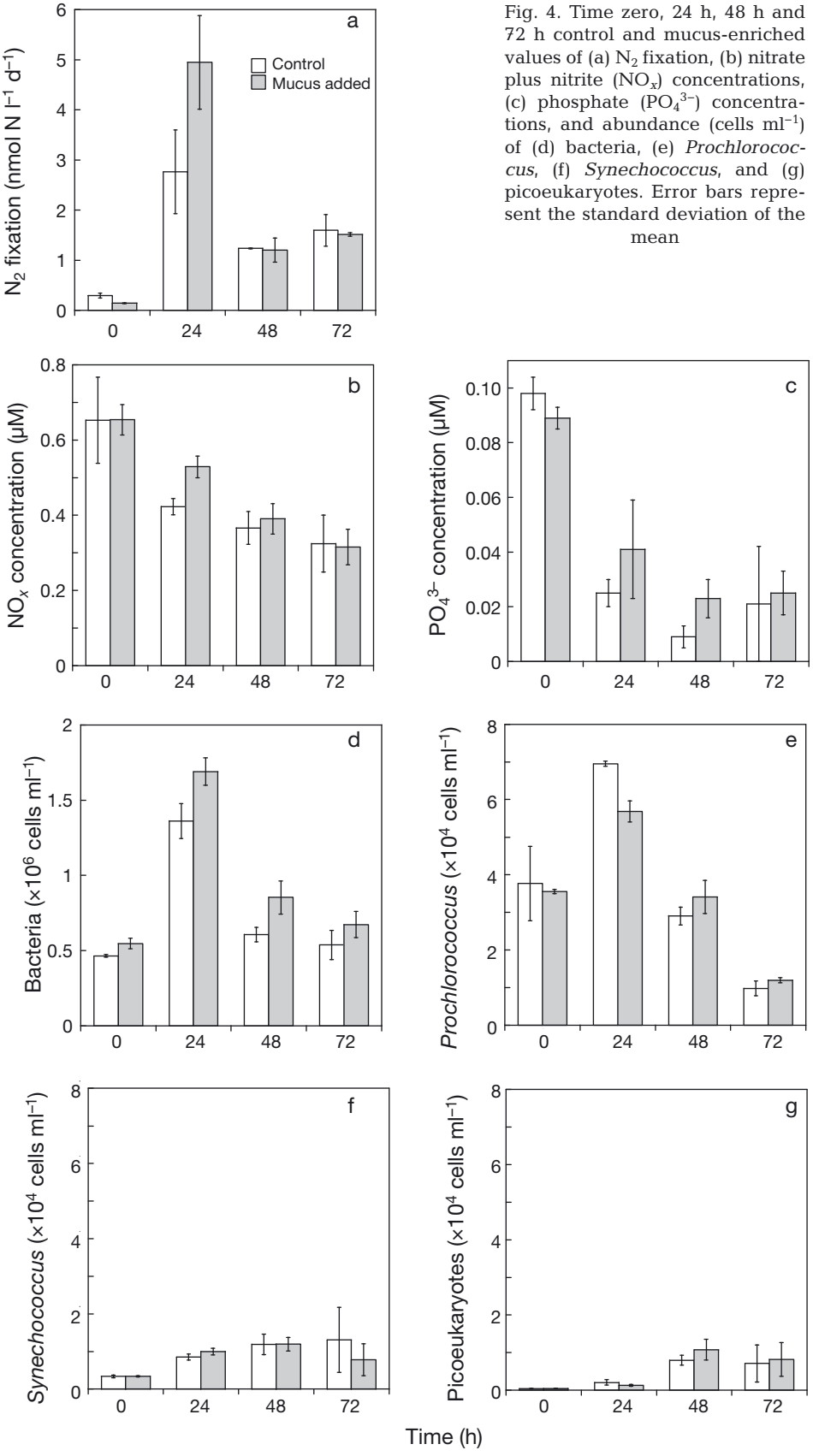

Fig. 4. Time zero, 24 h, 48 h and 72 h control and mucus-enriched values of (a) N_2 fixation, (b) nitrate plus nitrite (NO_x) concentrations, (c) phosphate (PO_4^{3-}) concentrations, and abundance (cells ml^{-1}) of (d) bacteria, (e) *Prochlorococcus*, (f) *Synechococcus*, and (g) picoeukaryotes. Error bars represent the standard deviation of the mean

coastal station (Stn D39) during our field experiments, this increase was not always significant. No increase was observed at the offshore station (Stn L2), except in February. Given the high organic matter content of mucus, it was expected that a significant increase of heterotrophic N_2 fixation activity would be observed as it was observed after addition of carbohydrates to open ocean seawater samples (e.g. Bonnet et al. 2013, Benavides et al. 2015). The high PO_4^{3-} content of mucus (see Table 1) is also known to enhance heterotrophic bacterial growth (Nakajima et al. 2015) and N_2 fixation in the New Caledonian lagoon (Berthelot et al. 2015). Our field-based results were consistent with the *in vitro* addition of mucus to seawater samples (mucus addition experiment), with N_2 fixation rates not significantly higher than those observed in the control treatments, i.e. where no mucus was added (Fig. 4a). This is despite the quantity of mucus added to clear seawater likely being much higher *in situ* after stressing corals as compared to the 2 ml added to 2.15 l samples during our *in vitro* experiment.

Our results contrast with previous studies that have observed active N_2 fixation in mucus particles released by corals in the Red Sea (Grover et al. 2014). There are at least 4 possible explanations for the lack of an enhancement of N_2 fixation activity. First, the chemical composition of the mucus during our experiments may have not been labile enough to trigger heterotrophic diazotrophic activity, as suggested by the high percentage of refractory carboxyl-rich alicyclic molecules (CRAM) present in these mucus samples (M. Benavides et al. unpubl. data). Moisander et al. (2012) found that the low N_2 fixation rates as well as growth rates of bacteria are due to a lack of energy given in the form of bioavailable carbon. The chemical composition of the mucus and its physical characteristics vary extensively among coral species and environmental conditions (Meikle et al. 1988, Rohwer et al. 2002, McKew et al. 2012), as well as depending on the collection strategy used, since artificially stressed corals release mucus which differs in composition to that released naturally (Ferrier-Pagès et al. 1998, Klaus et al. 2007, Tanaka et al. 2008), and as a result of its degradation over time following collection (Wild et al. 2004, Tanaka et al. 2011). While our experimental setup does not allow us to discern whether naturally released mucus would have caused a different diazotrophic response than mucus released after artificial stress, we believe that the degradation of mucus was minimal in our samples since <1 h passed between the time of collection and sample processing in the laboratory. Secondly, the dissolved organic carbon concentration of coral mucus ranges between ~300 and 4000 µM, with values as high as 7500 µM in some cases (Brown & Bythell 2005, Huettel et al. 2006, Tanaka et al. 2011); thus it is possible that the addition of 2 ml of mucus introduced to 2.15 l incubation bottles during our *in vitro* experiments may not have been enough to trigger heterotrophic N_2 fixation. The quantity of mucus released *in situ* after stressing natural coral colonies cannot be assessed with our data. Third, the low abundance of heterotrophic diazotrophs in the waters of the New Caledonian lagoon (Turk-Kubo et al. 2015) could prevent the observation of any significant effects upon DOM (coral mucus) additions. Moreover, the phylotype-targeted quantitative PCR quantifications of Turk-Kubo et al. (2015) do not necessarily cover the overall diversity of heterotrophic diazotrophs present in the lagoon's waters. Nevertheless, the heterotrophic diazotrophs dominate over autotrophic ones on a global basis (Farnelid et al. 2011). Finally, other sources of DOM to the Caledonian lagoon, such as riverine and atmospheric sources (Mari et al. 2007, 2014), may alleviate organic carbon limitation in heterotrophic plankton. Indeed, a recent study suggests that heterotrophic bacteria within the New Caledonian lagoon are more limited by nitrogen than by carbon (Van Wambeke et al. 2015). The effect of DOM on heterotrophic planktonic diazotrophs may vary seasonally according to DOM composition (organic carbon and nitrogen content) and its bioavailability.

Although mucus did not affect pelagic N_2 fixation rates in our study, it caused an increase in diazotrophic abundance in the column water whatever the season. This increase is due to high abundance of diazotrophs inside the mucus which are introduced in the column water upon its release. The activity of these diazotrophs seemed to be low, not affecting N_2 fixation rates in the surrounding waters. Moreover, the mucus did affect the abundance of heterotrophic bacteria in general as previously observed (Huettel et al. 2006). It is thus likely that non-diazotrophic heterotrophic bacteria grew faster than diazotrophic ones in our experiment, which is not surprising given that NO_x concentrations were not totally exhausted in lagoon waters at the time of the mucus addition experiment (Fig. 4b). As it requires ~25% more energy to reduce N_2 (87 kcal) than nitrate (69 kcal) to ammonium (Falkowski 1983), it is thus not surprising that heterotrophic diazotrophs did not fix N_2, or were less competitive than non-diazotrophs given that nitrate was not depleted. Nevertheless it is possible that the proportion of heterotrophic diazotrophs present in sea-

water was not sufficient to observe a change in the N_2 fixation rates (Turk-Kubo et al. 2014).

Moreover, the variability in abundance and activity of diazotrophs was likely affected by temperature (Shiozaki et al. 2014, 2015). Except in February, N_2 fixation rates were highest at higher temperatures. The differences in temperature observed between the 2 stations sampled agreed with those of Ouillon et al. (2005) and were likely caused by the more efficient water renewal closer to the reef barrier as compared to the coastal station. These differences led to a water warming and to a greater development of diazotrophs at Stn D39 than at Stn L2. The abundance and community composition of diazotrophs in the tropical Southwest Pacific have been shown to be related to changes in temperature, with greater abundances at temperatures above 25°C (Garcia et al. 2007, Bonnet et al. 2015b) and it is likely that N_2 fixation is influenced by environmental conditions rather than by coral mucus in this region. Negative and positive linear relationships have been found between the abundance of UCYN-A and UCYN-B and temperature, respectively (Moisander et al. 2010, Bonnet et al. 2015a). Nevertheless, the abundance and activity of diazotrophs in the present study were generally lower than those observed in previous studies (e.g. Biegala & Raimbault 2008, Turk-Kubo et al. 2015). Biegala & Raimbault (2008) observed UCYN abundances ~3-fold higher than those observed in April in our study, and Bonnet et al. (2015b) measured N_2 fixation rates of ~10 nmol N l^{-1} d^{-1} in February 2013 close to Stn L2 (i.e. 70-fold higher than the rates recorded in our study in the same season). This may be due to the specific location where our experiments were performed (in shallow waters, and very close to the coast for Stn D39), thus harboring NO_x concentrations known to inhibit N_2 fixation (Holl & Montoya 2005, Knapp 2012), whereas the stations sampled in the studies mentioned above were located in the middle of the lagoon where water flow is more constant (Ouillon et al. 2010) and NO_x concentrations lower (Fichez et al. 2010). Nevertheless, during our study NO_x concentrations at the coastal station D39 were 2-fold lower than at Stn L2, suggesting a diminished influence of the Dumbea River runoff during this season.

Coral mucus harbors important UCYN and rhizobia communities

Corals form mutualistic associations with diverse prokaryotic communities including diazotrophs (Olson et al. 2009, Reis et al. 2009) which have been found in the skeleton (Shashar et al. 1994, Davey et al. 2008), tissue (Lesser et al. 2007, Lema et al. 2014) and mucus of corals (Lema et al. 2012). The high heterogeneity of diazotroph communities living within the mucus of corals such as *Acropora* sp. (Nithyanand et al. 2011, Lema et al. 2012) likely provides a significant source of fixed nitrogen for corals and the wider reef ecosystem (Cardini et al. 2014). Moreover, diazotrophs inhabiting coral mucus matrices may play a key role in coral health (Reis et al. 2009). Although we only quantified UCYN and rhizobia, these 2 groups provide a good representation of the diazotrophic communities associated to coral reefs as they have often been identified in several coral species of the Southwest Pacific such as *Acropora* sp., which were the dominant coral species of our sampling sites (Lema et al. 2012, 2014, Krediet et al. 2013), and are also abundant in the pelagic compartment of tropical waters (Biegala & Raimbault 2008, Le Moal et al. 2011). The abundance of diazotrophs within the mucus was always higher than in the water column whatever the season (Figs. 2g,h & 3g,h). This was especially notable in winter, when diazotrophs were scarce in surrounding waters. The permanent high abundance of diazotrophs within the coral mucus suggests that these microorganisms are important for the nitrogen nutrition of the coral holobiont and for the water column (Lema et al. 2012, Cardini et al. 2015).

Although our mucus samples contained abundant diazotroph populations when compared to seawater samples (Figs. 2 & 3), the lack of statistically significant differences between seawater and seawater containing mucus N_2 fixation rates (Fig. 1) suggests that these colonizing diazotrophs were not especially active, or at least not more active than planktonic diazotrophs. These results contrast with those of Grover et al. (2014), who found significant N_2 fixation rates in mucus flocs. The activity and community composition of coral-associated microbes are highly dynamic and we do not discount that N_2 fixation activity by mucus-colonizing diazotrophs provides an important source of nitrogen in coral reef ecosystems under environmental conditions different to those present during our study (Rädecker et al. 2015). Planktonic N_2 fixation influenced by coral mucus release may in turn influence benthic communities. Knapp et al. (2015) have shown that the largest fraction of primary production within the New Caledonian lagoon is sustained by N_2 fixation in the water column and exported to benthic communities, either directly through diazotroph micro-

organism sedimentation (Bonnet et al. 2015b) or indirectly through fixed N_2 transfer to non-diazotrophic microorganisms and consequent sedimentation. This is confirmed by a recent study showing that diazotrophs significantly contribute to the nitrogen nutrition of both corals and zooxanthellae (M. Benavides et al. unpubl. data).

CONCLUSIONS

The diversity of active N_2 fixation sites present in coral reef ecosystems (e.g. hard and soft corals, seagrasses, sediments and sponges) indicates that diazotrophic activity provides an important source of combined nitrogen to these ecosystems. While planktonic N_2 fixation is also important in coral lagoon waters, our results suggest that this activity is not strongly influenced by organic materials released by corals such as mucus. However, our results do show that coral mucus harbors abundant diazotrophic communities that are released into the water column and may provide an additional source of fixed nitrogen to the pelagic coral reef ecosystem. In contrast to the diazotrophic communities in the seawater column which varied greatly over time, the abundance of diazotrophs within the mucus remained stable over the study period, and ~20- to ~400-fold higher than seawater abundances, in summer and winter, respectively (Figs. 2 & 3). Together these results indicate a key role for diazotrophs associated with the coral holobiont. Diazotrophs also influence the pelagic and benthic compartments within the reef ecosystems as they are released into the seawater associated with mucus and subsequently undergo sedimentation.

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LITERATURE CITED

Adjeroud M, Fernandez JM, Carroll AG, Harrisson PL, Penin L (2010) Spatial patterns and recruitment processes of coral assemblages among contrasting environmental conditions in the southwestern lagoon of New Caledonia. Mar Pollut Bull 61:375–386

Agawin NSR, Benavides M, Busquets A, Ferriol P, Stal LJ, Arístegui J (2014) Dominance of unicellular cyanobacteria in the diazotrophic community in the Atlantic Ocean. Limnol Oceanogr 59:623–637

Allers E, Niesner C, Wild C, Pernthaler J (2008) Microbes enriched in seawater after addition of coral mucus. Appl Environ Microbiol 74:3274–3278

Bednarz VN, Cardini U, van Hoytema N, Al-Rshaidat MMD, Wild C (2015) Seasonal variation in dinitrogen fixation and oxygen fluxes associated with two dominant zooxanthellate soft corals from the northern Red Sea. Mar Ecol Prog Ser 519:141–152

Benavides M, Moisander PH, Berthelot H, Dittmar T, Grosso O, Bonnet S (2015) Mesopelagic N_2 fixation related to organic matter composition in the Solomon and Bismarck Seas (Southwest Pacific). PLoS ONE 10:e0143775

Berthelot H, Moutin T, L'Helguen S, Leblanc K and others (2015) Dinitrogen fixation and dissolved organic nitrogen fueled primary production and particulate export during the VAHINE mesocosm experiment (New Caledonia lagoon). Biogeosciences 12:4273–4313

Biegala IC, Raimbault P (2008) High abundance of diazotrophic picocyanobacteria (<3 µm) in a Southwest Pacific coral lagoon. Aquat Microb Ecol 51:45–53

Bonnet S, Biegala IC, Dutrieux P, Slemons LO, Capone DG (2009) Nitrogen fixation in the western equatorial Pacific: rates, diazotrophic cyanobacterial size class distribution, and biogeochemical significance. Glob Biogeochem Cycles 23:GB3012, doi:10.1029/2008GB003439

Bonnet S, Dekaezemacker J, Turk-Kubo KA, Moutin T and others (2013) Aphotic N_2 fixation in the eastern tropical South Pacific Ocean. PLoS ONE 8:e81265

Bonnet S, Rodier M, Turk-Kubo K, Germineaud C and others (2015a) Contrasted geographical distribution of N_2 fixation rates and *nif*H phylotypes in the Coral and Solomon Seas (southwestern Pacific) during austral winter conditions. Global Biogeochem Cycles 29: 1874–1892

Bonnet S, Berthelot H, Turk-Kubo K, Fawcett S, Rahav E, L'Helguen S, Berman-Frank I (2015b) Dynamics of N_2 fixation and fate of diazotroph-derived nitrogen in a low nutrient low chlorophyll ecosystem results from the VAHINE mesocosm experiment (New Caledonia). Biogeosciences Discuss 12:19579–19626

Brown BE, Bythell JC (2005) Perspectives on mucus secretion in reef corals. Mar Ecol Prog Ser 296:291–309

Capone DG, Zehr JP, Paerl HW, Bergman B, Carpenter EJ (1997) *Trichodesmium*, a globally significant marine cyanobacterium. Science 276:1221–1229

Cardini U, Bednarz VN, Foster RA, Wild C (2014) Benthic N_2 fixation in coral reefs and the potential effects of human-induced environmental change. Ecol Evol 4:1706–1727

Cardini U, Bednarz VN, Naumann MS, van Hoytema N and others (2015) Functional significance of dinitrogen fixation in sustaining coral productivity under oligotrophic conditions. Proc R Soc B 282:20152257

Casareto BE, Charpy L, Langlade MJ, Suzuki T, Ohba H, Niraula M, Suzuki Y (2008) Nitrogen fixation in coral reef

environments. In: Proc 11th Int Coral Reef Symp, Ft. Lauderdale, FL, 7–11 July 2008, session number 19, p 896–900

Charpy L, Palinska KA, Abed RMM, Langlade MJ, Golubic S (2012) Factors influencing microbial mat composition, distribution and dinitrogen fixation in three western Indian Ocean coral reefs. Eur J Phycol 47:51–66

Davey M, Holmes G, Johnstone R (2008) High rates of nitrogen fixation (acetylene reduction) on coral skeletons following bleaching mortality. Coral Reefs 27:227–236

Den Haan J, Visser PM, Ganase AE, Gooren EE and others (2014) Nitrogen fixation rates in algal turf communities of a degraded versus less degraded coral reef. Coral Reefs 33:1003–1015

Falkowski PG (1983) Enzymology of nitrogen assimilation. In Carpenter EJ, Capone DG (eds) Nitrogen in the marine environment. Academic Press, New York, NY, p 839–868

Farnelid H, Andersson AF, Bertilsson S, Al-Soud WA, Hansen LH (2011) Nitrogenase gene amplicons from global marine surface waters are dominated by genes of non-cyanobacteria. PLoS ONE 6:e19223

Ferrier-Pagès C, Gattuso JP, Cauwet G, Jaubert J, Allemand D (1998) Release of dissolved organic carbon and nitrogen by the zooxanthellate coral *Galaxea fascicularis*. Mar Ecol Prog Ser 172:265–274

Fichez R, Chifflet S, Douillet P, Gérard P and others (2010) Biogeochemical typology and temporal variability of lagoon waters in a coral reef ecosystem subject to terrigeneous and anthropogenic inputs (New Caledonia). Mar Pollut Bull 61:309–322

Furnas MJ (1992) The behavior of nutrients in tropical aquatic ecosystems. In: Connell DW, Hawker DW (eds) Land use patterns and nutrient loadings of the Great Barrier Reef Region. James Cook University, Townsville, p 162–179

Garcia N, Raimbault P, Sandroni V (2007) Seasonal nitrogen fixation and primary production in the Southwest Pacific: nanoplankton diazotrophy and transfer of nitrogen to picoplankton organisms. Mar Ecol Prog Ser 343:25–33

Großkopf T, Mohr W, Baustian T, Schunck H and others (2012) Doubling of marine dinitrogen-fixation rates based on direct measurements. Nature 488:361–364

Grover R, Ferrier-Pagès C, Maguer JF, Ezzat L, Fine M (2014) Nitrogen fixation in the mucus of Red Sea corals. J Exp Biol 217:3962–3963

Halm H, Lam P, Ferdelman TG, Lavik G and others (2012) Heterotrophic organisms dominate nitrogen fixation in the South Pacific Gyre. ISME J 6:1238–1249

Holl CM, Montoya JP (2005) Interactions between nitrate uptake and nitrogen fixation in continuous cultures of the marine diazotroph *Trichodesmium* (Cyanobacteria). J Phycol 41:1178–1183

Huettel M, Wild C, Gonelli S (2006) Mucus trap in coral reefs: formation and temporal evolution of particle aggregates caused by coral mucus. Mar Ecol Prog Ser 307:69–84

Jacquet S, Delesalle B, Torretón JP, Blanchot J (2006) Response of phytoplankton communities to increased anthropogenic influences (southwestern lagoon, New Caledonia). Mar Ecol Prog Ser 320:65–78

Kérouel R, Aminot A (1997) Fluorometric determination of ammonia in sea and estuarine waters by direct segmented flow analysis. Mar Chem 57:265–275

Klaus JS, Janse I, Heikoop JM, Sanford RA, Fouke BW (2007) Coral microbial communities, zooxanthellae and mucus along gradients of seawater depth and coastal pollution. Environ Microbiol 9:1291–1305

Knapp AN (2012) The sensitivity of marine N_2 fixation to dissolved inorganic nitrogen. Front Microbiol 3:374

Knapp AN, Fawcett SE, Martínez-Garica A, Leblond N, Moutin T, Bonnet S (2015) Nitrogen isotopic evidence for a shift from nitrate- to diazotroph-fueled export production in VAHINE mesocosm experiments. Biogeosciences Discuss 12:19901–19939

Krediet CJ, Ritchie KB, Paul VJ, Teplitski M (2013) Coral-associated micro-organisms and their roles in promoting coral health and thwarting diseases. Proc R Soc B 280: 20122328

Kulbicki M, Galzin R, Letourneur Y, Mou-Tham G and others (1996) Les peuplements de poissons de la réserve marine du recif Aboré (Nouvelle-Calédonie): composition spécifique, structures trophique et démographique avant l'ouverture à la pêche. Doc Sci Tech I, ORSTOM, Nouméa

Larkum AWD (1988) High rates of nitrogen fixation on coral skeletons after predation by the crown of thorns starfish *Acanthaster planci*. Mar Biol 97:503–506

Le Moal M, Collin H, Biegala IC (2011) Intriguing diversity among diazotrophic picoplankton along a Mediterranean transect: a dominance of rhizobia. Biogeosciences 8: 827–840

Lema KA, Willis BL, Bourne DG (2012) Corals form characteristic associations with symbiotic nitrogen-fixing bacteria. Appl Environ Microbiol 78:3136–3144

Lema KA, Willis BL, Bourne DG (2014) Amplicon pyrosequencing reveals spatial and temporal consistency in diazotroph assemblages of the *Acropora millepora* microbiome. Environ Microbiol 16:3345–3359

Lesser MP, Mazel CH, Gorbunov MY, Falkowski PG (2004) Discovery of symbiotic nitrogen-fixing cyanobacteria in corals. Science 305:997–1000

Lesser MP, Falcón LI, Rodríguez-Román A, Enríquez S, Hoegh-Guldberg O, Iglesias-Prieto R (2007) Nitrogen fixation by symbiotic cyanobacteria provides a source of nitrogen for the scleractinian coral *Montastraea cavernosa*. Mar Ecol Prog Ser 346:143–152

Luo YW, Doney SC, Anderson LA, Benavides M and others (2012) Database of diazotrophs in global ocean: abundances, biomass and nitrogen fixation rates. Earth Syst Sci Data 5:47–106

Mari X, Rochelle-Newall E, Torréton JP, Pringault O, Jouon A, Migon C (2007) Water residence time: a regulatory factor of the DOM to POM transfer efficiency. Limnol Oceanogr 52:808–819

Mari X, Lefèvre J, Torréton JP, Bettarel Y and others (2014) Effects of soot deposition on particle dynamics and microbial process in marine surface waters. Global Biogeochem Cycles 28:662–678

McKew BA, Dumbrell AJ, Daus SD, Hepburn L, Thorpe E, Mogensen L, Whitby C (2012) Characterization of geographically distinct bacterial communities associated with coral mucus produced by *Acropora* spp. and *Porites* spp. Appl Environ Microbiol 78:5229–5237

Meikle P, Richards GN, Yellowlees D (1988) Structural investigations on the mucus from six species of coral. Mar Biol 99:187–193

Mitchell R, Chet I (1975) Bacterial attack of corals in polluted seawater. Microb Ecol 2:227–233

Moisander PH, Beinart RA, Hewson I, White AE and others

(2010) Unicellular cyanobacterial distributions broaden the oceanic N_2 fixation domain. Science 327:1512–1514

Moisander PH, Zhang R, Boyle EA, Hewson I, Montoya JP, Zehr JP (2012) Analogous nutrient limitations in unicellular diazotrophs and *Prochlorococcus* in the South Pacific Ocean. ISME J 6:733–744

Moisander PH, Serros T, Paerl RW, Beinart RA, Zehr JP (2014) Gammaproteobacterial diazotrophs and *nifH* gene expression in surface waters of the South Pacific Ocean. ISME J 8:1962–1973

Montoya JP, Voss M, Kähler P, Capone DG (1996) A simple, high-precision, high-sensitivity tracer assay for N_2 fixation. Appl Environ Microbiol 62:986–993

Nakajima R, Yoshida T, Azman BAR, Zaleha K, Othman BHR, Toda T (2009) *In situ* release of coral mucus by *Acropora* and its influence on the heterotrophic bacteria. Aquat Ecol 43:815–823

Nakajima R, Tanaka Y, Yoshida T, Fujisawa T and others (2015) High inorganic phosphate concentration in coral mucus and its utilization by heterotrophic bacteria in a Malaysian coral reef. Mar Ecol (Berl) 36:835–841

Naumann MS, Richter C, el-Zibdah M, Wild C (2009) Coral mucus as an efficient trap for picoplanktonic cyanobacteria: implications for pelagic–benthic coupling in the reef ecosystem. Mar Ecol Prog Ser 385:65–76

Nithyanand P, Indhumathi T, Ravi AV, Pandian SK (2011) Culture independent characterization of bacteria associated with the mucus of the coral *Acropora digitifera* from the Gulf of Mannar. World J Microbiol Biotechnol 27: 1399–1406

Olson ND, Ainsworth TD, Gates RD, Takabayashi M (2009) Diazotrophic bacteria associated with Hawaiian *Montipora* corals: diversity and abundance in correlation with symbiotic dinoflagellates. J Exp Mar Biol Ecol 371: 140–146

Ouillon S, Douillet P, Fichez R, Panché JY (2005) Enhancement of regional variations in salinity and temperature in a coral reef lagoon, New Caledonia. C R Geosci 337: 1509–1517

Ouillon S, Douillet P, Lefevre JP, Le Gendre R and others (2010) Circulation and suspended sediment transport in a coral reef lagoon: the south-west lagoon of New Caledonia. Mar Pollut Bull 61:269–296

Rädecker N, Pogoreutz C, Voolstra CR, Wiedenmann J, Wild C (2015) Nitrogen cycling in corals: the key to understanding holobiont functioning? Trends Microbiol 23: 490–497

Ramm J, Lupu A, Hadas O, Ballot A, Rucker J, Wiedner C, Sukenik A (2012) A CARD-FISH protocol for the identification and enumeration of cyanobacterial akinetes in lake sediments. FEMS Microbiol Ecol 82:23–36

Reis AMM, Araújo SD, Moura RL, Francini-Filho RB and others (2009) Bacterial diversity associated with the Brazilian endemic reef coral *Mussismilia braziliensis*. J Appl Microbiol 106:1378–1387

Riemann L, Farnelid H, Steward GF (2010) Nitrogenase genes in non-cyanobacterial plankton: prevalence, diversity and regulation in marine waters. Aquat Microb Ecol 61:235–247

Rix L, Bednarz VN, Cardini U, van Hoytema N, Al-Horani FA, Wild C, Naumann MS (2015) Seasonality in dinitrogen fixation and primary productivity by coral reef framework substrates from the northern Red Sea. Mar Ecol Prog Ser 533:79–92

Rohwer F, Seguritan V, Azam F, Knowlton N (2002) Diversity and distribution of coral-associated bacteria. Mar Ecol Prog Ser 243:1–10

Shashar N, Cohen Y, Loya Y, Sar N (1994) Nitrogen fixation (acetylene reduction) in stony corals: evidence for coral–bacteria interactions. Mar Ecol Prog Ser 111:259–264

Shiozaki T, Kodama T, Furuya K (2014) Large-scale impact of the island mass effect through nitrogen fixation in the western South Pacific Ocean. Geophys Res Lett 41: 2907–2913

Shiozaki T, Nagata T, Ijichi M, Furuya K (2015) Nitrogen fixation and the diazotroph community in the temperate coastal region of the northwestern North Pacific. Biogeosciences 12:4751–4764

Shnit-Orland M, Kushmaro A (2009) Coral mucus-associated bacteria: a possible first line of defense. FEMS Microbiol Ecol 67:371–380

Sorokin YI (1993) Coral reef ecology. Springer, Berlin

Tanaka Y, Miyajima T, Ogawa H (2008) Bacterial degradability of dissolved organic carbon in coral mucus. In: Proc 11th Int Coral Reef Symp, Ft. Lauderdale, FL, 7–11 July 2008, session number 19, p 945–949

Turk-Kubo KA, Karamchandani M, Capone DG, Zehr JP (2014) The paradox of marine heterotrophic nitrogen fixation: abundances of heterotrophic diazotrophs do not account for nitrogen fixation rates in the Eastern Tropical South Pacific. Environ Microbiol 16:3095–3114

Turk-Kubo KA, Frank IE, Hogan ME, Desnues A, Bonnet S, Zehr JP (2015) Diazotroph community succession during the VAHINE mesocosms experiment (New Caledonia Lagoon). Biogeosciences Discuss 12:9043–9079

Van Wambeke F, Pfreundt U, Barani A, Berthelot H and others (2015) Heterotrophic bacterial production and metabolic balance during the VAHINE mesocosm experiment in the New Caledonia lagoon. Biogeosciences Discuss 12:19861–19900

Wiebe WJ, Johannes RE, Webb KL (1975) Nitrogen fixation in a coral reef community. Science 188:257–259

Wild C, Huettel M, Klueter A, Kremb SG, Rasheed MYM, Jørgensen BB (2004) Coral mucus functions as an energy carrier and particle trap in the reef ecosystem. Nature 428:66–70

Wilkinson CR, Williams D, Sammarco PW, Hogg RW, Trott LA (1984) Rates of nitrogen fixation on coral reefs across the continental shelf of the central Great Barrier Reef. Mar Biol 80:255–262

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