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Nutrient status in coral reefs of the Îles Eparses (Scattered Islands): comparison to nearby reefs subject to higher anthropogenic influences (Mozambique Channel and Mascarenes, Indian Ocean)

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Abstract

Indian Ocean coral reef environments off Mascarenes (Réunion and Rodrigues Islands), Comores archipelago (Mayotte) and Eparses atolls (Europa, Glorieuses, Juan de Nova and Tromelin), were sampled in 2007 and 2009 for environmental parameters and benthic diatoms studies. This preliminary note documents the nutrient concentrations [NO₃, NO₂, PO₄ and Si(OH)₄] of coastal waters in diverse sites and examines the possible relationship between nutrient concentration and anthropogenic pressure. The pool of data is restricted, but the

marine coastal environments of Réunion, Rodrigues and Mayotte exhibit, on average, higher levels of nutrient concentration, as compared to Eparses atolls, probably in relation to the degree of urbanisation. A project based on the study of benthic diatom assemblages will offer the opportunity to search for possible anthropogenic signatures.

INTRODUCTION

The diversity of coral reef environments is universally recognized as high (e.g. Connel 1978, Done 1982, Richmond 1993, Edgar et al. 1997, Reaka-Kudla 1997, Knowlton 2001). Numerous theories explaining the high diversity of coral reefs have been proposed (e.g. Karlson and Hurd 1993, Fraser and Currie 1996). The Neutral Theory, which assumes that individuals are demographically identical regardless of species, has been refuted by Dornelas et al. (2006). Whatever the status, history and origin of this high diversity, several factors related to global change such as meteorological disturbances, long term climatic changes (Madin et al. 2008), and anthropogenic pressure (Mellin et al. 2008) are known to have detrimental effects on reefs. Coral reefs are highly susceptible to stress and disturbance (e.g. Banner 1974, Karlson and Hurd 1993), and particularly to temperature (Miller et al. 2009). El Niño is suspected to particularly affect reefs, i.e. in the east Pacific, inducing bleaching phenomenon (Glynn and D'Croz 1990, Huppert and Stone 1998).

Coral reef environments show high productivity and high diversity and are characterised by low levels of nutrients (oligotrophy) and high turnover via complex food webs (Goreau et al. 1979). But anthropogenic pressure induces dramatic changes in these environments (e.g. Richmond 1993, Dubinsky and Stambler 1996, Edinger et al. 1998, Knowlton 2001, Saffache 2002, Bellwood et al. 2004, Downs et al. 2005, Fichez et al. 2005). For example, an excess

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of inorganic nutrients due to domestic sewage release proved to be related to lagoon eutrophication and the proliferation of macroalgae (Hallock and Schlager 1986, Mohammed and Mgaya 2001, Lapointe et al. 2005). Macroalgae retain sediments, weaken the corals and, finally, may replace corals. Eutrophication can also induce mortality of corals by disturbing the physiology of zooxanthellae (Buchleim 1998). Indeed a certain resilience may exist "but human induced stress is evident" (Nyström et al. 2000). Several programs were developed to further the conservation of coral reefs, and to protect them via management strategies: e.g. Gourbesville and Thomassin (2000) proposed reconciling waste water management and ecological preservation, while Litter and Litter (2007) concluded that from a management perspective, levels of herbivory and nutrients rank among the most useful quantitative indicators of coral reef resilience.

The Îles Eparses (Scattered Islands), located close to Madagascar, are the fifth district of the French "Terres Australes et Antarctiques Françaises" and include small scattered atolls that are at present only inhabited by small groups of military personnel (Juan de Nova, Glorieuses and Europa, 15 persons on each atoll) and a meteorological team (Tromelin). A landing airstrip occupies a large area on each island. Tourism is occasionally allowed, but during the last century these islands have been occupied and their resources exploited (coprah plantation on Glorieuses, goat and rabbit breeding on Europa, guano exploitation on Juan de Nova) and their native vegetation has been more or less eliminated. Protecting these sanctuaries is therefore an important issue, with coral reefs and endemic inland fauna being the key targets. The EPARSES 2009 cruise (TAAF, N.O. Marion Dufresne II) permitted several scientific teams to approach these atolls and collect valuable samples pertaining to the environmental setting and biodiversity.

The COSADIME (COral SAnd DIatoms off Mascarenes and Eparses) project dealt with microphytobenthos and particularly benthic diatoms from coral sands of the Indian Ocean, with two objectives:

- 1) a recollection of Achnanthes taxa (Bacillariophyta) from Mascarenes (Riaux-Gobin et al. in press) and the Îles Eparses (Scattered Islands),
- 2) establishing the possible relationships between diatom assemblages and different levels of natural and anthropogenically altered trophic levels.

Nutrient concentrations (particularly NO_2 , NO_3 and PO_4) may give an indication of the level of eutrophication (natural organic recycling or anthropogenic disturbance) experienced by these particularly vulnerable ecosystems (cf. Buchleim 1998, Fichez et al. 2005, Lapointe et al. 2005). Cuet et al. (1988), Cuet (1994) and Vacelet et al. (1999), among others, pointed out these excesses in nutrients in Réunion and Mayotte respectively. This paper deals with and compares the inorganic nutrient status of Eparses, characterized by low anthropogenic pressure, to those of Mayotte and Mascarenes (e.g. Réunion and Rodrigues), which are subjected to greater anthropogenic influence (Amanieu et al. 1993, Jauze 1998, Bernard 2005).

MATERIALS AND METHODS

Sampling was performed for short periods in the reef lagoons of Réunion (June 2007, May 2009), Rodrigues (June 2007), Eparses and Mayotte (May 2009). Contrasting sites were selected to obtain samples from a broad range of environments, from brackish to marine, and from high tide pools to intertidal coral sands and mangrove environments (Table 1). Water temperature was measured with a Testo 735 ($\pm 0.05^\circ\text{C}$), and salinity and pH were measured with portable conductivity and pH meter probes (SP536: salinity ± 0.5 ; Portames 654 Knick: pH ± 0.02). For the nutrient survey, water samples above the sampled sediments were collected with a syringe (water depth from 5 to 10–20 cm, Table 1) and filtered with Whatman 0.45 μm GMF syringe filters. The filtrates were immediately poisoned with HgCl_2 (final concentration 0.66 mM), for later analyses in UMR7621 Banyuls/mer. Nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4) and silicic acid $[\text{Si}(\text{OH})_4]$ concentrations were measured (Autoanalyser SEAL AA3 HR) following Tréguer and Le Corre (1975), and results were expressed per liquid unit (μM , Table 1). In order to identify samples or groups of samples with comparable geochemistry, or which showed an obvious instability, and keeping in mind that the pool of data is restricted, a Principal Component Analysis (PCA, Statbox 6 from Grimmersoft) was used to represent original data (nutrients and sites) in a two dimensional space with minimal loss of information. Salinity was used as a supplementary variable (plotted in graphs but not used in the estimation of factors). Non-parametric PCA was performed since data did not follow a normal distribution. Site acronyms (Table 1) were as

Table 1

Geographical site position, environmental parameters (temperature (°C), pH, salinity, nutrient [PO₄, Si(OH)₄, NO₂, NO₃] concentrations, water depth), remarks. See text for acronyms.

Site	Latitude	Longitude	Temperature (°C)	pH	Salinity	PO ₄ (μM)	Si(OH) ₄ (μM)	NO ₂ (μM)	NO ₃ (μM)	water depth	Site remarks
EUROPA 22-24 April 2009											
EUR 01	22°20.308'S	40°21.312'E	22	7.94	34.8	0.05	2.19	0.05	0.16	10 cm	shallow marine sediment
EUR 02	"	"	21.95	7.47	34.8	0.10	3.35	0.07	0.29	10 cm	coral bank with algae
EUR 04	22°20.300'S	40°22.164'E	25.75	7.78	38.1	0.10	3.55	0.05	0.05	5-15 cm	shore pass to the mangrove, flood
EUR 05	22°20.306'S	40°21.729'E	25.4	8.54	47.5	0.09	4.06	0.07	0.21	5 cm	high tide rock pool, with mat, pink in surface and brown-green underneath (cyanobacteria)
EUR 051	22°20.865'S	40°22.350'E	19.95	6.52	39.5	0.88	5.15	0.12	1.33	20 cm	<i>Avicennia</i> spp. "small mangrove"
EUR 06	"	"	20.8	6.89	40.0	0.88	7.25	0.13	1.74	20 cm	idem inland site
EUR 64	"	"	27	7.6	48.0	0.26	5.62	0.04	0.11	5-10 cm	high tide pool, pink cover mat
*EUR 08	22°20.787'S	40°20.453'E	25.5	nd	33.7	1.52	14.53	1.20	13.13	10-20 cm	karstic lake, enteromorphae algae
EUR 09	22°23.800'S	40°22.327'E	nd	8.85	36.4	0.32	8.78	0.11	1.27	10 cm	intertidal marine sediment
EUR 10	22°20.686'S	40°20.008'E	24.55	nd	34.0	0.19	3.17	0.07	1.46	5-10 cm	rock pool, surf zone
EUR 11	22°22.956'S	40°20.787'E	nd	7.75	34.6	0.46	37.05	0.71	35.7	5-10 cm	inland karstic pool "Mare à Julie"
JUAN DE NOVA 26-29 April 2009											
JDN 01	17°02.798'S	42°43.673'E	25.5	7.14	34.2	0.11	4.12	0.04	0.39	2 cm	high tide level, white sand + pink material (cyanobacteria)
JDN 03	17°02.797'S	42°43.811'E	32.9	6.95	40.0	0.13	4.37	0.04	0.26	2 cm	sandy tubes and <i>Halimeda</i> spp.
JDN 04	17°02.784'S	42°43.696'E	27.4	7.17	34.7	0.09	2.92	0.09	0.54	5 cm	rock pool, cyanobacteria mat
JDN 05	"	"	27.4	7.21	34.7	0.45	20.9	0.27	8.75	2 cm	high tide level beach, fine sand
JDN 06	"	"	28.6	7.03	34.3	0.13	8.26	0.07	0.65	5 cm	shallow marine sediment with benthic green copepods
JDN 10	17°03.404'S	42°44.906'E	31.25	8.1	40.0	0.2	2.53	0.05	0.25	5 cm	shallow marine pool, fine sand
JDN 18	17°03.601'S	42°44.984'E	28.35	7.92	32.6	0.22	5.01	0.07	0.49	5 cm	beach, coarse sand, "Trou bleu"
JDN 19	"	"	27.95	7.95	35.3	0.31	1.12	0.10	0.70	2 cm	outflow from beach
*JDN 20	17°03.721'S	42°44.475'E	nd	7.83	25.7	2.60	9.11	0.45	10.83	5 cm	inland brackish pool
MAYOTTE 01-02 May 2009											
*MAY 01	12°47.486'S	45°08.262'E	30.0	8.2	8.5	0.74	435	0.21	4.08	5-20 cm	Bouyouini river, aërian roots
MAY 09	12°46.812'S	45°14.237'E	36.0	7.93	34.0	0.49	34.63	0.15	0.97	5 cm	near Mamoudzou harbour, lateritic marine mud, aërian roots
MAY 25	12°43.243'S	45°10.067'E	nd	nd	nd	0.26	7.33	0.10	1.27	30 cm	Longoni harbour, stone blocks
MAY 26	12°41.709'S	45°04.170'E	30.8	8.1	34.0	0.51	23.17	0.46	11.18	10 cm	Mtsamboro, brown sand beach, turbid lateritic water
MAY 29	12°46.809'S	45°15.570'E	nd	7.45	36.4	0.25	4.95	0.07	0.39	18 m	near Dzaoudzi, subtidal, divers
GRANDES GLORIEUSES 04-08 May 2009											
GLO 01	11°35.152'S	47°17.515'E	27.10	7.18	34.2	0.20	5.23	0.03	0.10	10 cm	beach, coral sand, ripple marks
GLO 03	11°35.092'S	47°17.396'E	25.55	7.08	34.2	0.07	2.46	0.04	0.10	10 cm	rock pool, high tide level
*GLO 05	11°34.502'S	47°17.350'E	35.10	7.29	30.0	1.38	113	1.25	149.43	10 cm	inland brackish karstic pool
GLO 07	11°34.066'S	47°17.921'E	27.0	7.64	34.1	0.30	2.79	0.03	1.24	5-10 cm	white sediment low tide, ripple marks
GLO 10	11°34.544'S	47°18.509'E	27.6	6.6	34.1	0.36	4.86	0.10	0.20	5-10 cm	low tide, old reef, egg smelling (cyanobacteria)
GLO 11	11°35.059'S	47°17.316'E	30.7	7.9	38.0	0.18	2.91	0.05	0.39	5 cm	low tide, shallow lagoon
LYS 01	11°30.993'S	47°22.600'E	nd	8.17	39.3	0.59	7.31	0.34	1.52	10 cm	central lagoon, East, Lys atoll
LYS 02	"	"	nd	7.88	34.6	0.09	4.99	0.17	2.39	5 cm	marine coral platform, Lys atoll
LYS 03	"	"	nd	7.93	37.0	0.79	4.62	0.10	0.16	10-15 cm	central lagoon, West, Lys atoll
TROMELIN 11 May 2009											
TRO 01	15°53.125'S	54°31.148'E	27.3	7.95	33.7	0.36	8.13	0.09	4.94	10-15 cm	inland shallow marine lagoon with macroalgae
TRO 02	15°53.046'S	54°31.090'E	27.8	nd	34.0	0.21	2.91	0.05	0.34	10-30 cm	beach, with swell
TRO 04	15°53.252'S	54°31.442'E	29.5	7.91	34.0	0.19	3.33	0.06	0.19	10 cm	rocky shore, diversified macroalgae
REUNION 15-18 May 2009											
REU01	21°22.060'S	55°32.800'E	nd	nd	34.0	0.14	4.76	0.06	0.82	20 cm	Grand Anse, marine bay, strong swell
REU02	21°10.258'S	55°17.167'E	nd	nd	34.0	0.22	14.47	0.09	1.96	20 cm	St Leu, high tide, beach
*REU03	21°20.345'S	55°27.483'E	nd	nd	34.0	0.93	366	0.20	182.65	30 cm	Ravine Blanche, coral platform, macroalgae
REU04	21°10.354'S	55°17.184'E	nd	nd	34.0	0.27	33.09	0.14	8.00	20 cm	St Leu, low tide, coral platform
REU05	21°10.055'S	55°17.206'E	nd	nd	34.0	0.15	30.70	0.15	3.76	10-20 cm	South St Leu, rocky shore, marine bay
RODRIGUES 03-07 June 2007											
ROD01	19°40.90'S	63°25.13'E	nd	nd	35.1	0.19	4.70	0.16	3.09	10 cm	Port Mathurin, marine, beach ripple marks
*ROD02	"	"	25.6	nd	27.4	0.85	90.00	1.27	18.8	5 cm	Port Mathurin, estuarine sediment
ROD03	19°40.59'S	63°26.08'E	27.5	nd	33.3	0.40	21.50	0.17	1.16	5-10 cm	Anse aux Anglais, marine, beach
ROD04	19°40.33'S	63°27.00'E	25.8	nd	35.4	0.50	15.40	0.11	2.36	5 cm	Anse aux Caves, mangrove mud
ROD05	19°40.59'S	63°26.08'E	23.7	nd	34.8	0.29	17.80	2.21	13.90	5 cm	Anse aux Anglais, marine, beach, macroalgae
ROD06	19°41.66'S	63°24.49'E	22.7	nd	36.0	0.24	18.10	1.55	1.44	5 cm	Baie aux Huîtres, mangrove, cyanobacteria
ROD07	19°41.16'S	63°24.00'E	22.7	nd	35.3	0.24	5.28	0.60	13.2	5 cm	East Anse au Diamant, rocky shore
*ROD08	19°40.59'S	63°26.08'E	24.3	nd	0.7	3.96	693	0.15	6.54	10 cm	Anse aux Anglais, river, inland upper stream
ROD09	19°45.00'S	63°25.99'E	25.4	nd	34.2	0.31	5.25	0.08	2.65	10 cm	Hermitage island, marine bay, macroalgae
ROD10	19°46.26'S	65°25.06'E	25.0	nd	35.5	0.28	1.83	0.14	0.66	5 cm	île aux Chats, marine sand, macroalgae
*ROD11	19°40.59'S	63°26.08'E	25.2	nd	0.2	1.96	725	0.33	3.57	5-10 cm	Rivière des Anglais, running spring
REUNION 10-15 June 2007											
REU06	21°10.258'S	55°17.167'E	27.4	nd	32.0	0.42	33.8	0.17	31.8	5-10 cm	South St Leu, beach, sand
REU07	21°16'S	55°29'E	26.7	nd	33.8	0.3	15.4	0.16	8.89	5-10 cm	St Pierre Ravine Blanche, beach, scoured sand
REU08	"	"	27.4	nd	32.2	0.33	32.9	0.09	14.7	5-10 cm	St Pierre Alizé plage, sandy beach and old reef
REU09	21°15'S	55°21'E	26.0	nd	33.1	0.25	25.0	0.1	4.25	5 cm	Etang Salé, rocky shore, old reef
REU10	20°59.9'S	55°16.5'E	24.3	nd	34.3	0.22	5.11	0.06	3.32	5-10 cm	St Gilles l'Hermitage, old reef
*REU11	21°4.7'S	55°14.3'E	26.4	nd	30.9	9.1	73.5	8.04	28.1	5 cm	St Gilles La saline, beach with fresh water input
*REU12	21°9.91'S	55°17.07'E	21.7	nd	12.0	1.49	345	0.61	65.9	5-10 cm	St Leu river, estuary
REU13	21°08'S	55°17'E	25.0	nd	34.4	0.37	1.66	0.08	1.57	10 cm	old reef, macroalgae

nd – no data

* = samples eliminated from PCA analysis 2 (see text and Fig. 2)

follows: JDN (Juan de Nova), EUR (Europa), GLO (Grandes Glorieuses main atoll), LYS (Lys Island, north of Grandes Glorieuses), TRO (Tromelin), MAY (Mayotte), REU (Réunion) and ROD (Rodrigues).

RESULTS AND CONCLUSIONS

The locations of sampling sites and data on environmental parameters and nutrients are given in Table 1. The brackish and fresh waters classically have high nutrient concentrations due to terrestrial discharge and organic mineralization, particularly via macroalgae decomposition (i.e. brackish karstic lakes in Eparses, rivers and mangroves, Table 1). Therefore, two distinct PCA were performed, the first one was conducted on the full data set ($n = 61$; Fig. 1) and the second one was conducted on a subset ($n = 51$; Fig. 2) obtained by eliminating samples with low salinity and high nutrient concentrations ($\text{NO}_3 > 36 \mu\text{M}$; e.g. brackish and freshwater samples and a highly polluted marine sample, REU03; * in Table 1).

For both analyses the first 2 factors explained 88% (Fig. 1) and 84% (Fig. 2) of the variance. The first factor (axis 1 on both figures) was strongly related to NO_2 , and to a lesser extent to NO_3 , and $\text{Si}(\text{OH})_4$ concentrations, while the second factor (axis 2) was mostly related to PO_4 concentrations with lower contributions from other variables.

The first analysis (full data set, Fig. 1) discriminates freshwater from brackish samples with high nutrient concentrations, and a $\text{NO}_3 : \text{PO}_4$ ratio (not shown) varying from relatively low values (positive scores on axis 2: from 3.1 for REU11 to 1.8 for ROD11) to very high values (negative scores on axis 2: from 44.2 for REU12, 108 for GLO05, to 196 for the marine sample REU03). The other data, mainly marine samples, are grouped at the center of Fig. 1.

The second analysis (subset, see above; Fig. 2) discriminates several groups of samples: one group (ellipse A), mostly corresponds to intertidal marine sites with low NO_3 and PO_4 , and high salinity, from GLO, JDN, EUR, and TRO, but also from other islands, such as Réunion (Grande Anse, REU01, an environment with rough swell and strong hydrodynamics). ROD10 (Rodrigues, île aux Chats) also had low nutrient concentrations, close to that from the Eparses atolls, most probably due to its location far from the main island and urbanisation hot spots.

Several samples grouped in ellipse B (Fig. 2) show relatively high NO_3 and $\text{Si}(\text{OH})_4$ concentrations and pertain to slightly brackish and apparently polluted sites from Réunion Island (REU08-06), an inland karstic lake on Europa (EUR11) and several lagoon sites from Rodrigues which are probably nutrient-enriched due to natural environmental conditions (large, shallow lagoon with low hydrodynamic exchange with the ocean).

ROD04, LYS01-03 and EUR51-06 (ellipse C in Fig. 2) pertain to mangrove systems and to the small, shallow, confined lagoon in the centre of Lys Island. Mangrove marine intertidal mud flats show a particular biogeochemistry (see Lacerda et al. 1995, Otero et al. 2006).

On average, nutrient concentrations in marine environments were lower on Eparses than on Réunion and Rodrigues Islands (Table 2). Among the four Eparses atolls, the marine samples off Glorieuses and Tromelin exhibited the lowest NO_3 concentrations. We can explain this through the geologic past of each sampled island: the old Eparses atolls are less subject to natural runoff than the younger volcanic systems, such as Réunion or Mayotte Islands. On the other hand, the Rodrigues reef system (much older and extensive than that of Réunion) is also subject to high anthropogenic pressure (Jauze 1998, Bernard 2005). Some marine beaches from Réunion which were particularly enriched with NO_3 are located close to urban areas (e.g. St Leu and St Pierre: REU03, REU06 and REU08) and are impacted by anthropogenic inputs. Several previous reports also highlighted such anthropogenic pollution, particularly near St Gilles (Cuet et al. 1988, Cuet 1989, Cuet 1994, Chazotte et al. 2002, Fichez et al. 2005). Marine embayments such as Port Mathurin and Anse aux Anglais in Rodrigues are also, but to a lesser extent, NO_3 enriched, possibly from the mineralization of sewage. As previously reported (e.g. Gourbesville and Thomassin 2000), some marine bays in Mayotte may also experience pollution via sewage (MAY26). Additionally, several biotopes were subject to natural eutrophication, such as the mangroves in Europa and Rodrigues and the karstic inland pools, which are highly enriched with organic material such as macroalgae and cyanobacteria (pers. obs.).

The coral reef lagoons off Eparses are particularly well preserved, with low nutrient levels, even if the reefs are not in good health everywhere (e.g. Juan de Nova, pers. obs.), while those in Réunion are partially polluted (see ref. cit., Amanieu et al. 1993). The

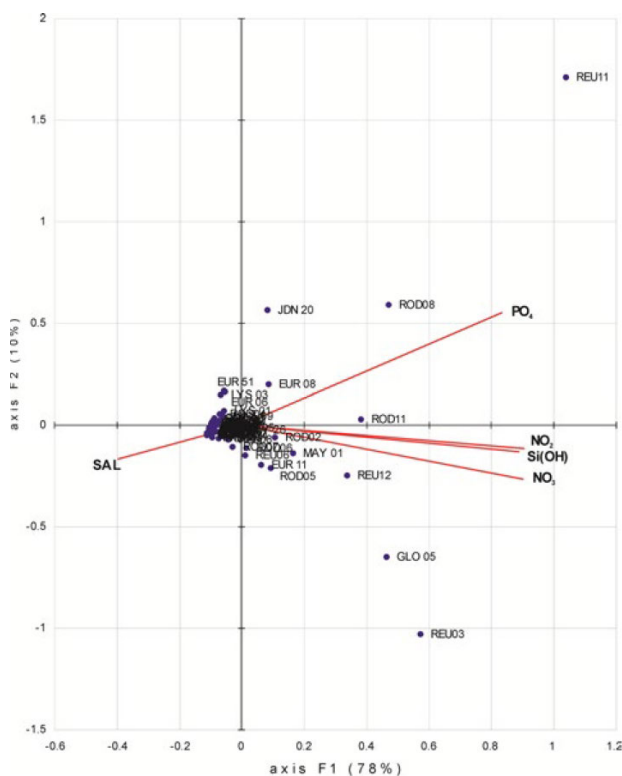


Fig. 1. PCA analysis performed on the full data set ($n = 61$). F1 F2 plan.

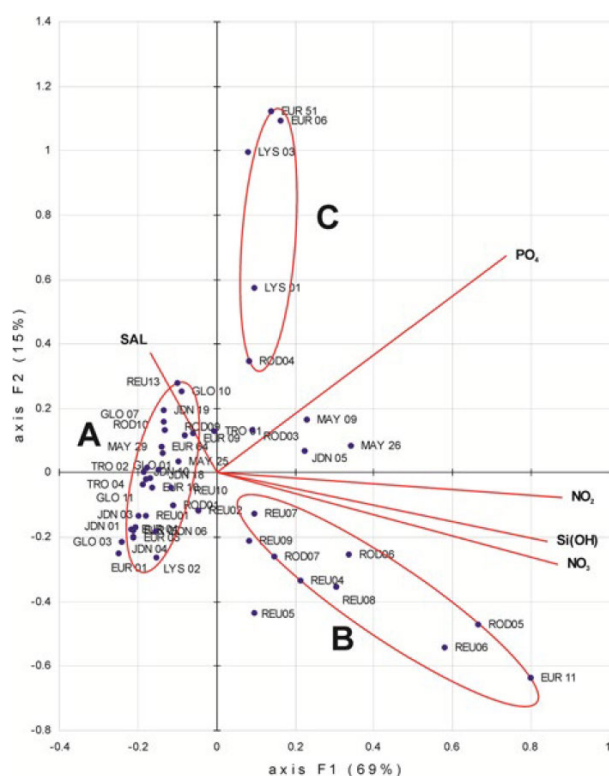


Fig. 2. PCA analysis performed on a subset ($n = 51$; see text). F1 F2 plan.

Table 2

Average nutrient concentration (μM) of marine samples of each group of islands [excluding brackish and freshwater samples (salinity < 32.2), highly polluted sites (REU03), karstic lake (EUR11) and Tromelin lagoon TRO01]. Mean and Standard deviation. See text for acronyms.

Site	Salinity	PO ₄	Si(OH) ₄	NO ₂	NO ₃
Low or no urbanisation					
EUR	39.30	0.32	4.79	0.08	0.74
	5.24	0.33	2.13	0.03	0.69
JDN	35.87	0.17	4.05	0.07	0.47
	2.94	0.08	2.27	0.02	0.18
GLO	34.92	0.22	3.65	0.05	0.41
	1.72	0.11	1.29	0.03	0.48
LYS	36.97	0.49	5.64	0.20	1.36
	2.35	0.36	1.46	0.12	1.12
TRO	34.00	0.20	3.12	0.06	0.27
High urbanisation					
MAY	34.6	0.38	17.52	0.20	3.45
	1.20	0.14	13.98	0.18	5.16
REU	33.95	0.24	16.27	0.11	4.07
	0.39	0.08	12.20	0.04	2.94
ROD	34.95	0.31	11.23	0.63	4.81
	0.85	0.10	7.70	0.81	5.48

recent inclusion of the latter as part of a Marine Protected Area ("Réserve Naturelle Marine", 3500 ha, with 5% as integral protected zone; see Brial 2010) gives some hope of their potential recovery or at least for a halt to their continued degradation.

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