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## Endangered New Caledonian endemic mushroom coral *Cantharellus noumeae* in turbid, metal-rich, natural and artificial environments

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## ABSTRACT

Since its description in 1984, little attention has been paid to the New Caledonian endemic mushroom coral *Cantharellus noumeae* (Fungiidae), an IUCN Red-listed, endangered coral species. Our study presents the first ever quantitative assessment conducted on *C. noumeae* populations for two contrasting sites in the same turbid bay. Sites differed by their substrates of artificial or natural origins. Metal concentrations of superficial sediment were measured. *C. noumeae* was found in high densities in metal-rich and turbid environments at both locations, reaching up to 288 individuals per 50 m<sup>2</sup>. It was 3.5 times more abundant on natural rock than on artificial substrates. Recruitment was also higher proportionally on rock (47% vs 7–14%). The composition of the associated coral communities included 30–37 species occurring in low densities. Our findings clarify the environmental niche of this species and its colonization potential, in order to eventually better characterize its conservation status.

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### 1. Introduction

New Caledonia (NC) is a French overseas territory located in the Western South Pacific Ocean. NC comprises a large land mass (Grande-Terre) and a few archipelagoes in close proximity (e.g. Loyalty Islands, Entrecasteaux Atolls). Since 2008, large sections of the coral reefs and lagoon have been included in the UNESCO World Heritage list (Andréfouët and Wantiez, 2010). The 36,000 km<sup>2</sup> of reefs and lagoons of NC present a large array of geomorphological diversity (Andréfouët et al., 2009), including deep turbid bays exposed to relief erosion and pollution by soils, which are naturally rich in metals (Ouillon et al., 2010). The NC economy is driven by nickel mining and the country is currently the third largest producer in the world. Mining is also seen as the main threat to New Caledonian coral reefs and lagoons since open-cast mining, as practiced here, increases the transfer of terrigenous particles into the adjacent coral reef lagoons (Bird et al., 1984).

NC is one of the world's marine biodiversity hotspots, mostly because of its coral reefs (Roberts et al., 2002). Coral reefs have been the subject of a considerable number of studies and harbor one of the

highest numbers of identified marine species in the world, predominantly owing to their habitat heterogeneity and coral-associated fauna (Hoeksema, 2007). The latest compendium for NC reported a total of 8783 known marine species (Payri and Richer de Forges, 2006) but this number is likely underestimated (Bouchet et al., 2002). Thus far, 401 scleractinian coral species from 17 families have been recorded (Lasne, 2010). Two-thirds of these species belongs to only four coral families, namely Acroporidae (30%), Merulinidae (18%), Fungiidae (13%) and Poritidae (7%).

Fungiidae, or mushroom corals, are restricted to the Indo-Pacific and include 52 species worldwide according to recent taxonomic revisions (Hoeksema, 1989, 2014; Gittenberger et al., 2011; Benzoni et al., 2012) and represent a substantial contribution to the total number of NC scleractinian species diversity. In NC, 53 fungiid species have been recorded (Lasne, 2010), but this listing did not take into account the recent taxonomic revisions, and contained various synonyms, misidentifications, and misspelled species names.

Mushroom corals represent a frequently overlooked component of the ecology of Indo-Pacific reefs. These mostly free-living corals are excellent pioneers in colonizing soft substrates that cannot be inhabited by attached coral species (Hoeksema, 2012a, 2012b). They are important for the initial settlement of reefs, because their dead skeletons can serve as substrate for other corals, making sandy bottoms more

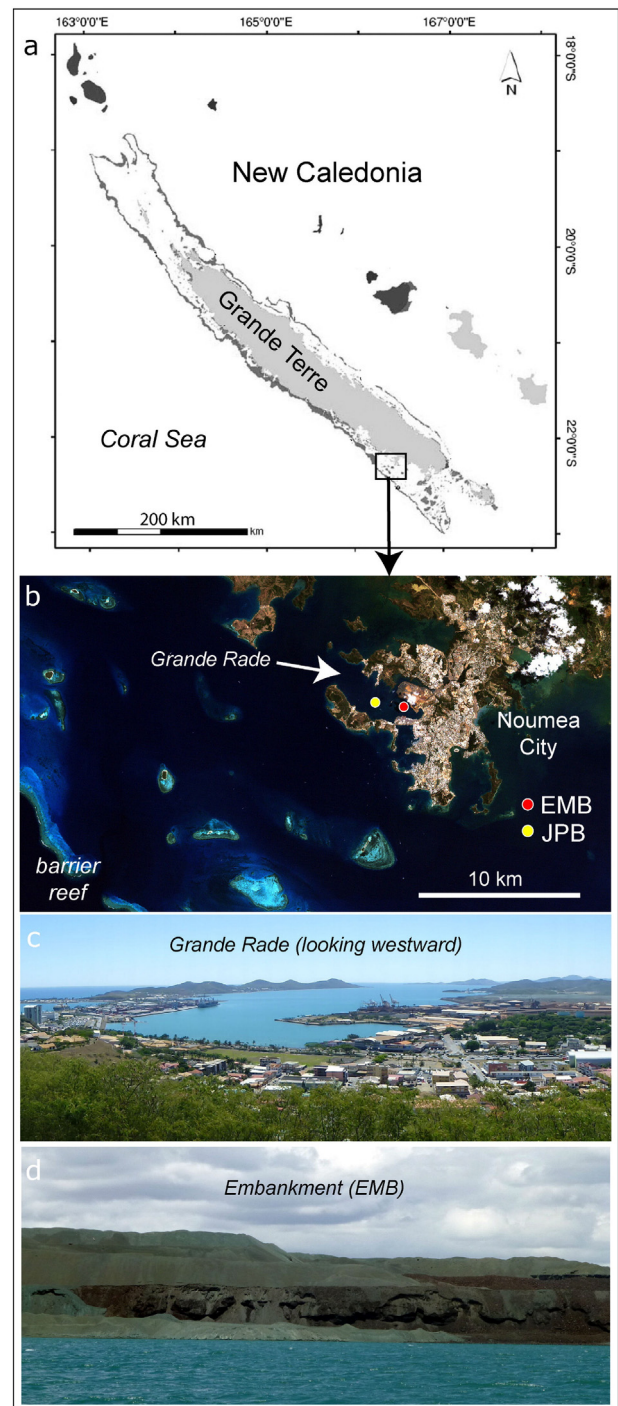
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inhabitable and suitable for colonization by other species (Sheppard, 1981). Most Fungiidae are characterized by their free mode of life as adults, with only an initial attached phase after settlement, the so-called anthocaulus stage (Hoeksema, 1989; Hoeksema and Gittenberger, 2010; Hoeksema and Benzoni, 2013). However, a total of 12 species remain attached during their entire life span (Benzoni et al., 2012). These species belong to the genera *Lithophyllon*, *Podabacia*, *Cycloseris* and *Cantharellus* (Gittenberger et al., 2011). *Cantharellus* comprises three species: *Cantharellus noumeae* (Hoeksema and Borel Best, 1984), which is the type species, *Cantharellus doederleini* (Marenzeller, 1907) and *Cantharellus jebbi* (Hoeksema, 1993). These three species have all restricted geographic distribution ranges and are predominantly monostomatous, attached, and cup-shaped or encrusting (Hoeksema, 1989, 1993). *C. noumeae* is currently considered endemic to NC, although it may also be represented in the fossil record from the Indonesian part of Borneo (Hoeksema, 1989; N.K. Santodomingo and B.W. Hoeksema, pers. obs.). There are unconfirmed records from other localities (Veron, 2000; Fenner and Muir, 2007), but they seem to be based on misidentified specimens. No substantiated records are known from the most nearby reef areas, such as the Great Barrier Reef (DeVantier et al., 2006; Hoeksema, 2015) and Vanuatu (Hoeksema, 2012c).

Fungiidae have the lowest proportions of threatened species (Carpenter et al., 2008), but *C. noumeae* is considered endangered by the IUCN Red list (Hoeksema et al., 2008). Although it is known that this solitary species is restricted to hard substrata in silty and muddy habitats, to date there is still very little detailed information on its geographical distribution, quantitative population abundance and size structure. The current records in NC are restricted to the north-western part and north-eastern part of Grande-Terre, the fringing and submerged reefs near Nouméa (the capital of NC), and to the southwest and south part of Grande-Terre. The latter includes Prony Bay (Fig. 1), a large protected bay now harboring a large mining complex, and the Loyalty Islands (Hoeksema and Borel Best, 1984; Fenner and Muir, 2007; F. Benzoni and B.W. Hoeksema, pers. obs.). Considering these few records and the large number of biodiversity expeditions and reef coral surveys in NC that have occurred during the last decade (e.g. Pichon, 2006; Fenner and Muir, 2007; Adjeroud et al., 2010; Lasne, 2010; Fenner, 2011), it seems that only a narrow range of conditions is suitable for the species. Specifically, enclosed bays with high sedimentation rates are a common denominator for all records, in depth ranges varying from ~5 to slightly over 30 m. These environmental conditions are not unique to *C. noumeae* since several scleractinian corals in New Caledonia can thrive in very turbid conditions and metal-rich environment. In these environments, they can form flourishing communities settled on either hard substrates covered by silty sediment or on soft substrates (Catala, 1958, 1964; Wijisman-Best, 1972; Laboute, 1988; Borsa et al., 2009).

Recently, during a survey in the main commercial and industrial harbor of New Caledonia, a large population of *C. noumeae* was observed at two close sites: a natural subtidal patch reef (or bank, as they are called in NC) and an artificial embankment next to a mining complex. This provided an unprecedented opportunity to measure for the first time the population structure of *C. noumeae* at two contrasting sites and to describe the associated coral communities. Field investigations dedicated to *C. noumeae* are needed to obtain more precise quantitative and systematic population data, abundances and preferred habitats, in order to eventually derive a niche model that is useful to generalize the distribution of this species and assess potential threats. Specifically, we designed the assessment to provide for both sites:

1. the population structure of the endemic species *C. noumeae*
2. the associated coral community composition
3. the quality of the environment. Given the high metal concentration in benthic sediments in New Caledonia, we characterized the superficial sediment and metal concentrations at both sites. In addition, a nearby site outside the main harbor was used for reference.



**Fig. 1.** Study site locations (a, b, c, d). a) New Caledonia and surrounding islands and reefs (atoll lagoons in black, barrier reef and patch reef in dark gray, land in light gray). b) Nouméa City and the Grande Rade location shown with a Landsat satellite image. c) View of the urban, harbor and nickel processing environment of the Grande Rade. d) View of the accumulation of scoria that characterizes the embankment (EMB) site.

As such, this research reports on the first quantitative assessment ever conducted on this endangered coral species.

## 2. Material and methods

### 2.1. Study area

The study area is the main harbor of Nouméa, called “la Grande Rade” (Fig. 1). It is situated in a bay that is significantly polluted by

heavy metals, including nickel (Ni), chrome (Cr), zinc (Zn), and cobalt (Co) (Dalto et al., 2006). It is also very turbid (Ouillon et al., 2010). The harbor receives both urban and industrial effluents generated mainly by the nickel industry (Breau, 2003). A large nickel processing factory is located on the northern shore of Grande Rade and a commercial harbor is located in the south (Fig. 1). The nickel processing factory is built on a reclaimed embankment (EMB). A regular bathymetric gradient is observed with an average depth of 20 m in the middle and entrance of the Grande Rade Bay to very shallow near the coastline. Fine sediments cover most of the bay except for the central Japanese Bank (JPB), where some hard substratum offers settlement space for corals. EMB and JPB are less than 2 km away from each other.

The EMB is made of hard artificial materials on top of a sandy bottom covered by mud deposits (Feuille et al., 1982; Ouillon et al., 2010). The southwestern limit of this reclaimed embankment was established more than 10 years ago, a timescale compatible with coral recruitment and growth. It is made of an accumulation from small-size compacted scoria (Fig. 1), a by-product of the nickel extraction process. Occasionally the EMB elevation is subject to change as new scoria is added, which makes the slope prone to landslides.

To be able to compare the harbor environment with a less anthropogenically impacted site, the nearby bay of Baie Maa (MAA) located 9 km northeast from the Grande Rade was selected as reference site. This area was previously used to make comparisons of metal concentrations with the harbor (Hédouin et al., 2011). This is a bay bordered by vegetation and without urbanized watersheds.

The EMB and JPB locations were assessed for their coral communities, with a total of four sites altogether. One site was surveyed at JPB at an average depth of 12 m. Three sites were surveyed at EMB: the flat shallow part (EMB\_3 at 3 m depth), the slope (EMB\_6 at 6 m depth) and the bottom (EMB\_9 at 9 m depth).

## 2.2. Coral community sampling and analysis

In March 2014, quantitative and qualitative data on coral species were collected using non-destructive techniques. Coral-dominated benthic assemblages were surveyed with SCUBA at each of the four sampling sites. Each site was surveyed using three randomly placed  $50 \times 1 \text{ m}^2$  belt-transects (English et al., 1997; Hoeksema, 2012a).

In each belt-transect, all corals (including *C. noumeae*) were photographed with a reference scale for identification and corallum size measurement. Identifications that were difficult to achieve in the field were confirmed to the species or genus level. Corals were generally identified using Veron and Pichon (1976, 1980), Veron et al. (1977), Hoeksema (1989), Wallace (1999), and Veron (2000). However, coral systematics have been subject to major revisions (Benzoni et al., 2012 and references therein). The with taxonomic nomenclature at genus and family level has been modified in order to follow an evolutionary based classification. We used the latest taxonomic references, especially for representatives of the former families Faviidae Gregory, 1900, Mussidae Ortmann, 1890, Trachyphylliidae Verrill, 1901, Oculinidae Gray, 1847, and Agariciidae Gray, 1847. In such cases, we followed Stolarski et al. (2011), Budd et al. (2012), Arrigoni et al. (2014), Benzoni et al. (2014), Huang et al. (2014a, 2014b), and Terraneo et al. (2014).

*C. noumeae* corals were counted in each  $50 \text{ m}^2$  belt-transect considering three size classes: small (S)  $\emptyset \leq 1.5 \text{ cm}$ ; medium (M)  $1.5 < \emptyset \leq 4.0 \text{ cm}$ ; large (L)  $\emptyset > 4.0 \text{ cm}$ . These categories were selected as the maximum adult size did not exceed 6.5 cm and also to possibly discriminate different life stages (juvenile, adult and old) (Hoeksema and Borel Best, 1984).

From the census, abundances ( $N$ ) were derived for each coral species. At each site the total number of species ( $S$ ) was counted and the Margalef diversity index ( $d$ ) (Margalef, 1958) was computed.  $N$ ,  $S$  and  $d$  did not account here for *C. noumeae*. This species dominated

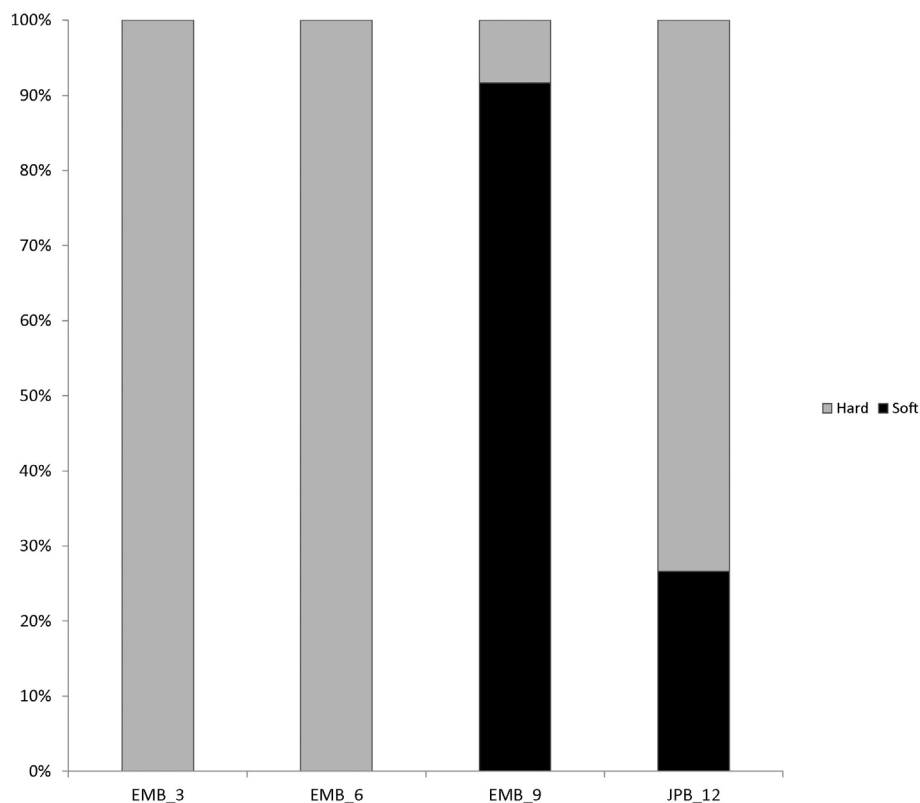


Fig. 2. Mean proportion of hard and soft substrata at each site. EMB\_3 = embankment 3 m depth; EMB\_6 = embankment 6 m depth; EMB\_9 = embankment 3 m depth JPB\_12 = Japanese Bank 12 m depth.

the overall community abundance and occurred in each transect and site. Differences in  $N$ ,  $S$  and  $d$  between sampling sites were determined using one-way Analysis of Variance (ANOVA) after testing for homogeneity of variances by Levene's test. Post hoc pair-wise comparison using the Tukey HSD test was applied to establish differences between groups. Similarities or dissimilarities in coral composition were analyzed independently with non-metric Multidimensional Scaling (MDS) plots and by hierarchical cluster analysis of a Bray–Curtis dissimilarity matrix of presence/absence species data. Analysis of Similarity (ANOSIM) was applied to establish significant differences in coral composition between sites and locations. Where differences existed, Similarity Percentage Breakdown (SIMPER) was used to detect which coral species contributed to the difference. Taxa were listed in decreasing order by their average contribution to the total average dissimilarity, with a cutoff at 50%. All similarity analyses were performed using PRIMER 6 statistical software groups (Clarke and Warwick, 2001).

Abundance data of *C. noumeae* were square root transformed to meet the assumptions of normality and homogeneity of variance. Normality was visually assessed with a normal probability plot and variance homogeneity was statistically tested with a Levene's test. Spatial variations were analyzed using one-way ANOVA tests with "Site" as a random factor. When spatial variations were identified, a Tukey's HSD post hoc statistical test was performed to determine which pairs of stations showed significant differences. All abundance analyses were performed using STATISTICA 9 (Statsoft, Tulsa, Oklahoma).

### 2.3. Sediment sampling and analysis

The cover of hard and soft substratum was visually estimated by Point Intercept Transect (PIT) every 0.5 m along the 50 transect line (Hill and Wilkinson, 2004).

For each of the four sites, a single sediment sample was randomly taken with a lightweight stainless steel Van-Veen grab (capacity 1.8 L) ensuring minor disturbance of the sediment top layer. The centimetric surface layer of oxidized sediments was retrieved, placed in single-use vinyl bags (Whirl-pack), and frozen for storage before being freeze-dried. Freeze-dried sub-samples were separately packaged for geochemical and sedimentological analyses. Concentrations of heavy metals (Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) were analyzed by ICP-OES (Optima 3300 FD, Perkin Elmer) following Fernandez et al. (2006).

For granulometry analyses, samples were dried, weighed and sieved on a vibrating granulometric column using the following mesh sizes in  $\emptyset$  units: 2000  $\mu\text{m}$ –200  $\mu\text{m}$ –50  $\mu\text{m}$ . The three fractions obtained were expressed as weight percentage of the initial bulk sample.

## 3. Results

### 3.1. Habitat description

The EMB slope was steep and quickly reached the 9-m depth. The flat shallow part and the slope consisted entirely of hard substratum (Fig. 2) whereas the lower sea floor was almost entirely soft bottom (91%). The hard substratum was composed of small-sized compacted scoria to blocks and boulders (Fig. 3). This was in contrast with the flat Japanese Bank (JPB) where the hard substratum at 12 m (73%) was loose dead coral rubble covered by a thin sediment layer.

### 3.2. Abundance of *C. noumeae*

The total abundance of *C. noumeae* was significantly different between the EMB and JPB locations ( $p = 0.03$ ) (Fig. 4). At JPB, abundance averaged  $N = 288 \pm 156$  (mean  $\pm$  SD) colonies per 50  $\text{m}^2$ . This was 3.5 times higher than the observed mean abundance on the EMB embankment ( $N = 82 \pm 93$ ) for all depths combined.

Abundance per size class (Fig. 4) also differed significantly between locations for size S ( $p < 0.001$ ) and size M ( $p = 0.02$ ). No significant differences were observed for size L ( $p = 0.63$ ). At JPB, *C. noumeae* abundances reached  $N = 138 \pm 81$  and  $N = 138 \pm 73$  colonies per 50  $\text{m}^2$  respectively for size S and size M. In comparison, the embankment abundances were lower, especially for size S, with 18 times less abundance ( $N = 7.3 \pm 7.2$ ).

Significant differences in abundance were observed between sites for size S ( $p = 0.001$ ) (Fig. 5). Paired analyses show that Japanese Bank abundances were significantly higher than at all other sites. Conversely, there were no differences between the embankment sites for size S. Size class M abundance (Fig. 5) also had significant differences among sites, namely between the JPB and EMB\_9 ( $p = 0.02$ ) with the latter showing the lowest abundance ( $N = 8.7 \pm 9.0$ ). Similarly, the larger class size displayed statistical differences ( $p = 0.03$ ) between EMB\_6 and EMB\_9 (Fig. 5), which had the highest ( $N = 85 \pm 53$ ) and the lowest density ( $N = 6.0 \pm 5.3$ ) for that class size, respectively.

Despite the differences of abundance, the size class frequency data showed that the three embankment sites had a similar population size structure (Fig. 6), with a low contribution (between 7 and 14%) of size S. Conversely, the Japanese Bank population was characterized by a

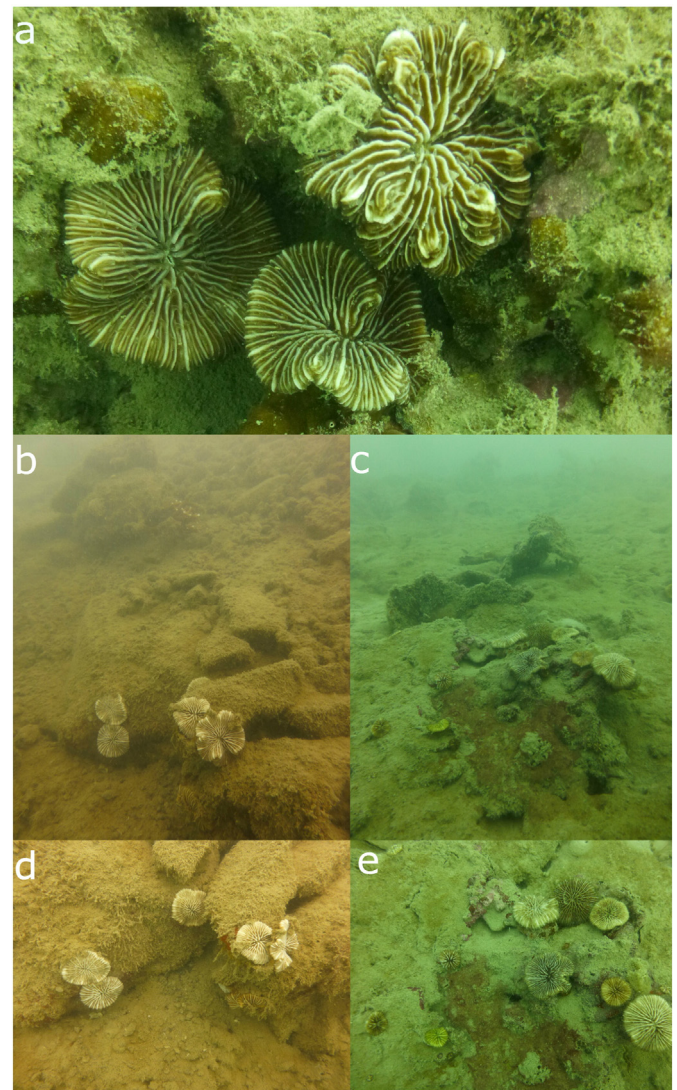


Fig. 3. Underwater pictures of a typical *Cantharellus noumeae* habitat found on the Japanese Bank (a, c, e) and the embankment (b, d). a) Close-up of *C. noumeae* corals; b–c) typical hard bottom substrate. d–e) Examples of *C. noumeae* aggregations.

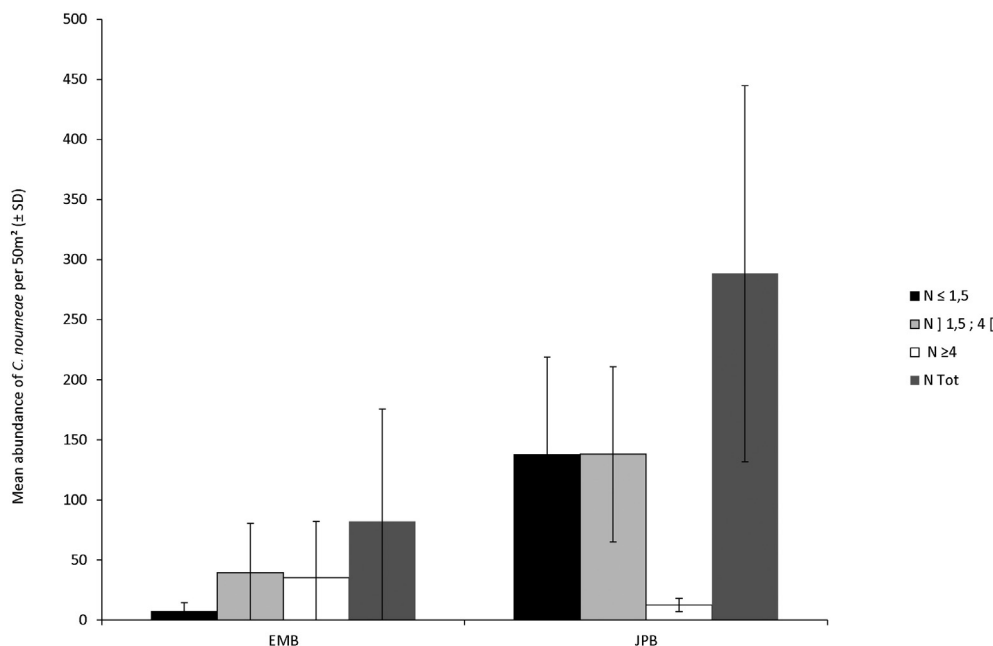


Fig. 4. Mean abundance of *Cantharellus noumeae* (±SD) per 50 m<sup>2</sup> for each size class (N) (cm) and for all sizes at each location. EMB = embankment; JPB = Japanese Bank.

high contribution of size S (47%) and a low contribution of size L (5%). Contribution of size M was relatively similar among the sites of the two locations (between 46% and 59%).

### 3.3. Composition of coral communities

Overall, the coral communities were characterized by low, though highly variable, living coral cover and high patchiness, with colonies growing on the scattered available hard substrate several centimeters, if not meters, apart. Except for *C. noumeae*, most species encountered in each belt-transect were actually rare, i.e., between 1 and 5 colonies (for 81% of the coral species at JPB, 95% at EMB\_3, 63% at EMB\_6, 100% at EMB\_9, and 60% at EMB in total).

At JPB at 12 m depth, in addition to *C. noumeae*, 37 scleractinian coral species were observed in total within the transects (Table ESM1). Among these, the most abundant were *Acropora kirstyae* forming branching thickets, *Montipora* sp., *Pachyseris speciosa*, *Stylophora pistillata*, and *Dipsastraea danae*. Noteworthy, the last three, together with *Merulina ampliata*, *Mycedium elephantotus*, *Stylocoeniella guentheri*, *Montipora* sp., and *Goniopora* sp1. had the highest contribution to the average similarity within this site and yielded altogether a cumulative percentage of similarity of 67%.

At EMB, a total of 30 scleractinian coral species were observed: 18 at EMB\_3, 24 at EMB\_6, and 8 at EMB\_9 (Table ESM1). The most abundant coral taxon other than *C. noumeae* encountered at all depths at this site was *Porites* spp., which contributed alone to 19.5% of the total within-site

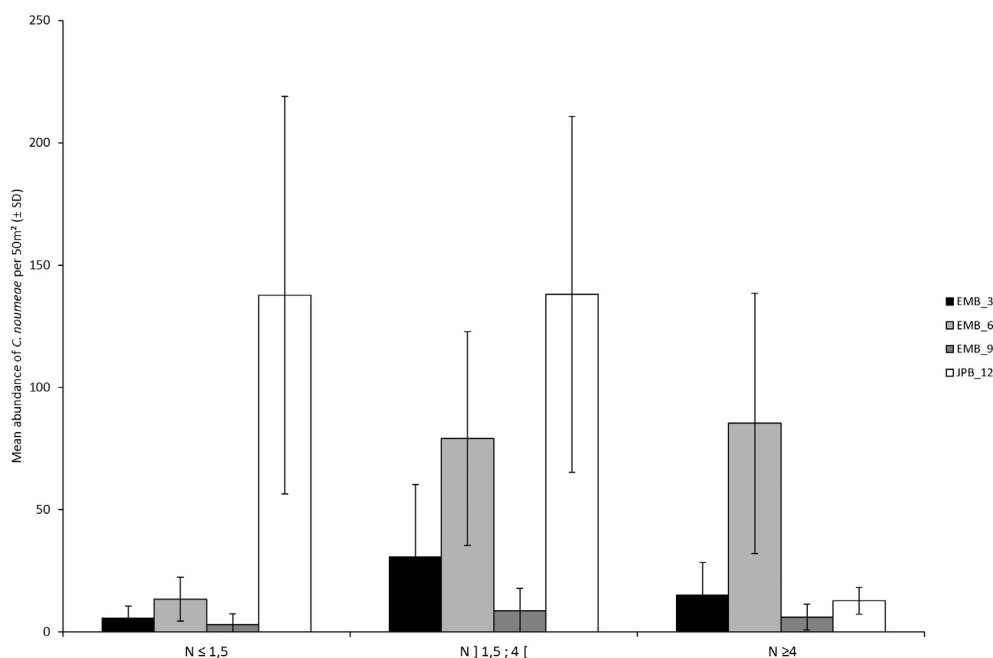
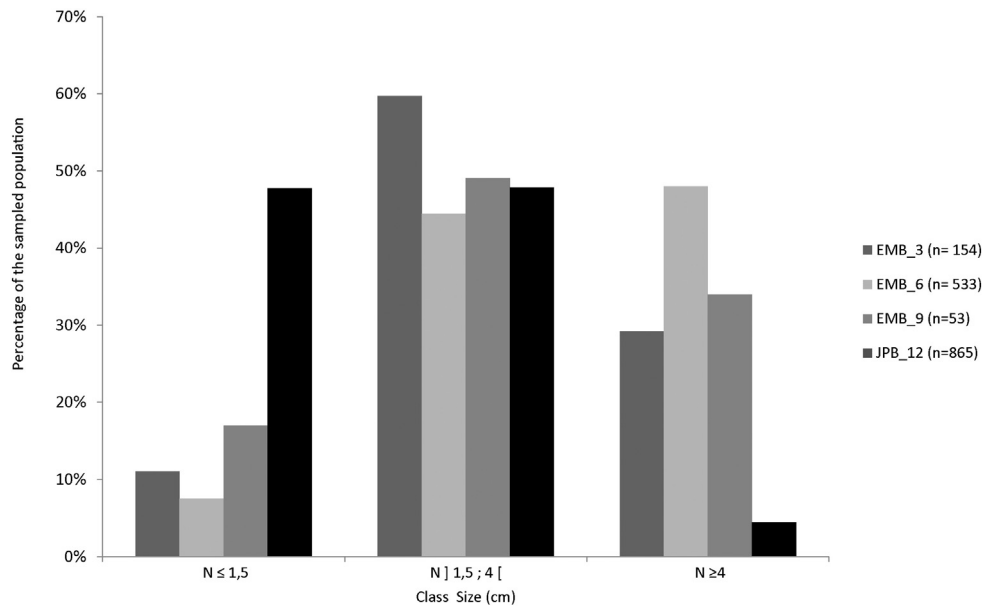


Fig. 5. Mean abundance of *Cantharellus noumeae* (±SD) per 50 m<sup>2</sup> for each class size (cm) and for all sizes at each sampling site. a) Size class S (Ø ≤ 1,5 cm); b) size class M; c) size class L (Ø > 4 cm); EMB\_3 = embankment 3 m depth; EMB\_6 = embankment 6 m depth; EMB\_9 = embankment 9 m depth; JPB\_12 = Japanese Bank 12 m depth.

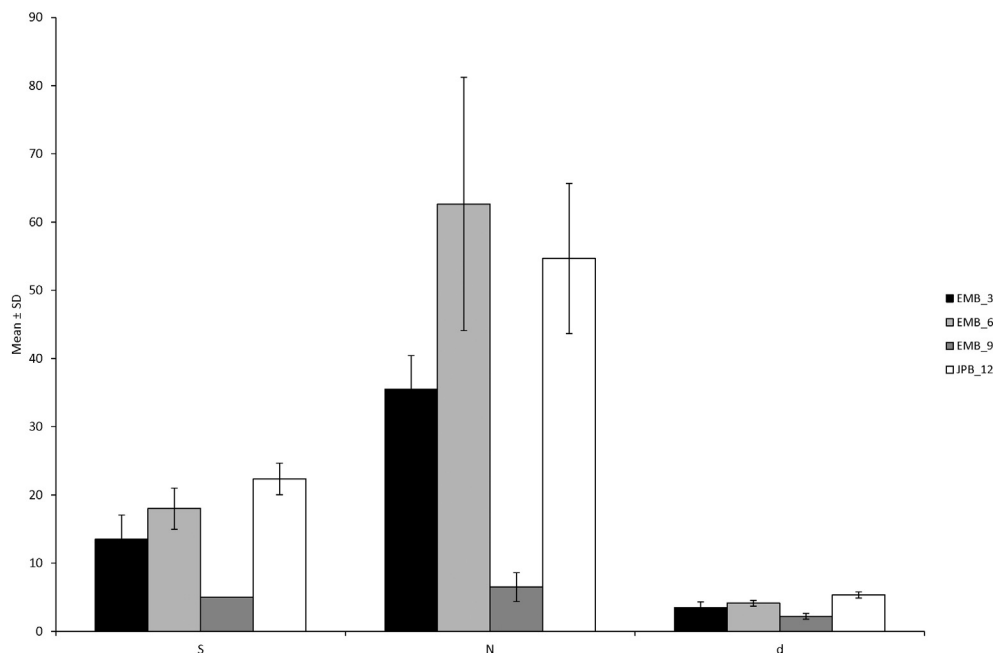


**Fig. 6.** Class size frequency of *Cantharellus noumeae* per site. EMB\_3 = embankment 3 m depth; EMB\_6 = embankment 6 m depth; EMB\_9 = embankment 3 m depth; JPB\_12 = Japanese Bank 12 m depth. n = sample size.

similarity across depths and represented 39% of the coral colonies at EMB. Colonies of this genus were seldom large boulders. More than half of the observed colonies at each depth were larger than 5 cm in diameter. At 3 m depth, only *Cyphastrea cf serailia* and *Dipsastraea cf speciosa* significantly contributed together with *Porites* spp. to the average similarity within site. At 6 m depth at EMB, besides *Porites* spp. and *C. noumeae*, the most abundant coral species were the encrusting *Pseudosiderastrea tayami* and the massive merulinids *Dipsastraea pallida*, *Dipsastraea matthaii* and *Goniastrea cf edwardsi*. These last three species together with *D. cf speciosa*, *S. guentheri*, *Turbinaria peltata* and *Montipora* sp. all equally contributed to over 50% of the within-site similarity. The deepest station at EMB (9 m) was characterized by the scarcity of corals, with *Porites* spp. on their own contributing to half of the within-site similarity.

Significant differences were found among all four sites for  $S$  ( $p = 0.002$ ),  $N$  ( $p = 0.012$ ) and  $d$  ( $p = 0.003$ ) (Fig. 7). The Japanese Bank (JPB\_12) had the highest average number of coral species with  $S = 22.3 \pm 2.3$ , and was significantly different from EMB\_3 and EMB\_9, but not from EMB\_6. EMB\_9 was significantly different from the other sites and depths, and had the lowest average species number ( $S = 5.0 \pm 0$  SD). No significant differences in  $S$  were found between EMB\_3 ( $S = 13.5 \pm 3.5$ ) and EMB\_6 ( $S = 18.0 \pm 3$ ).

Similar conclusions arose for abundance data ( $N$ ) on EMB. At JPB, coral abundance ( $N = 54.7 \pm 11.0$ ) was not significantly different from EMB\_6 ( $N = 62.7 \pm 18.6$ ) and EMB\_3 ( $N = 35.5 \pm 4.9$ ). EMB\_9 had the lowest abundance of corals ( $N = 6.5 \pm 2.1$ ). All EMB depths were significantly or almost ( $p < 0.06$ ) different from each other, with the highest abundance for EMB\_6 ( $N = 62.7 \pm 18.6$ ).



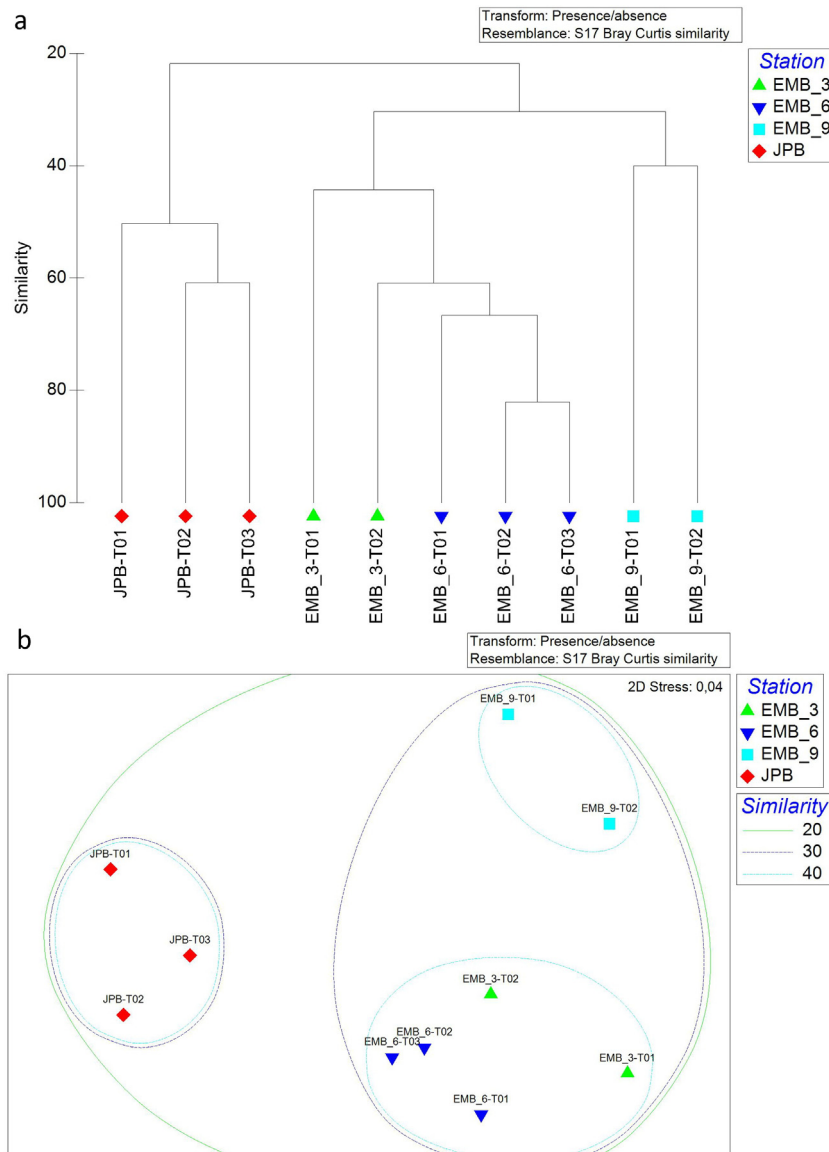
**Fig. 7.** Average ( $\pm$ SD) abundance ( $N$ ) and total number of coral species other than *Cantharellus noumeae* ( $S$ ), and Margalef diversity index ( $d$ ) per 50 m<sup>2</sup> for each sampling site. EMB\_3 = embankment 3 m depth; EMB\_6 = embankment 6 m depth; EMB\_9 = embankment 3 m depth; JPB\_12 = Japanese Bank 12 m depth.

The Margalef diversity index ( $d$ ), which combines  $S$  and  $N$ , yielded consistent results with  $N$ , but differences were more significant. JPB had the highest diversity index with  $d = 5.4 \pm 0.5$ , and was significantly different from all other stations at EMB. Among the embankment stations, significant paired differences in  $d$  were found, except between EMB\_3 ( $d = 3.4 \pm 0.9$ ) and EMB\_9 ( $d = 2.2 \pm 0.4$ ). EMB\_6 had the highest EMB diversity index with  $d = 4.1 \pm 0.4$ .

The multivariate analyses confirmed the strong differences in species composition between JPB and EMB, and between EMB\_9 and the rest of the embankment stations (Fig. 8). The cluster analysis and dendrogram (Fig. 8a) and the MDS plot (Fig. 8b) provided consistent groupings of transects and showed these differences. Furthermore, the ANOSIM analysis confirmed that coral species composition differed significantly between locations (Global  $R = 0.796$ ,  $p = 0.008$ ) and between all sites (Global  $R = 0.885$ ,  $P = 0.0002$ ). The average Bray–Curtis dissimilarity between EMB and JPB was high and reached 78%. Percentage breakdown (SIMPER) between locations is detailed per coral species (Table 1). Between sites, the similarity percentages from SIMPER

(Table 2) showed that EMB\_3 and EMB\_6 were the closest, with an average similarity of 52.6%. In contrast, JPB and EMB\_9 had the highest dissimilarity values with an average of 84.4%. This was close to the dissimilarity between EMB\_3 and JPB (83.1%).

A total of 13 coral genera and 21 species of corals (five of which were found only once) were encountered at JPB but not at EMB (Table ESM1). Among these, two species for each of the genera *Leptoseris*, *Goniopora*, *Psammocora* and *Echinopora*, and also for *S. pistillata*, all typically found in the calm and protected lagoon embayments in New Caledonia, were counted exclusively in the three transects at JPB but not at EMB. Conversely, five coral genera and 15 species (two of which found only once) were counted in the transects at EMB but not at JPB (Table ESM1). These were predominantly merulinids (five species of *Dipsastraea*, *Trachyphyllia* and *Caulastrea*) but also species of *Turbinaria*. Within the genus *Acropora*, out of the five species recorded during this study, *A. kirstyae* was only recorded at JPB, *Acropora lokani* and *Acropora muricata* were only found at EMB, while *Acropora vaughani* and *Acropora pulchra* were observed at both sites. The relative



**Fig. 8.** a) Dendrogram showing the group-averaged hierarchical clustering (CAH) of 10 transects at four sites (EMB\_3; EMB\_6; EMB\_9 and JPB) at two locations (EMB and JPB) based on the species composition (presence/absence) of hard coral assemblages. b) Ordination of 50 m<sup>2</sup> belt-transects at the four sites using multidimensional scaling (MDS) plots based on the CAH (b).

**Table 1**

SIMPER analyses of coral communities based on presence/absence data at the reclaimed embankment (EMB) and Japanese Bank (JPB) of the Grande Rade. Average dissimilarity between EMB (all depths) and JPB is 78.17%. F = species frequency within the site; % = percentage contribution; and  $\Sigma\%$  = cumulative percentage contribution. Numbers in bold indicate coral species exclusively found at one of the two sites.

Coral species	F EMB	F JPB	%	$\Sigma\%$
<i>Dipsastraea danae</i>	0.0	<b>1.0</b>	3.7	3.7
<i>Stylophora pistillata</i>	0.0	<b>1.0</b>	3.7	7.5
<i>Goniopora</i> sp. 1	0.0	<b>1.0</b>	3.7	11.2
<i>Mycidium elephantotus</i>	0.1	1.0	3.3	14.5
<i>Turbinaria</i> sp. 1	<b>0.9</b>	0.0	3.1	17.6
<i>Pachyseris speciosa</i>	0.3	1.0	2.9	20.4
<i>Turbinaria peltata</i>	<b>0.7</b>	0.0	2.6	23.0
<i>Echinopora</i> cf. <i>lamellosa</i>	0.0	<b>0.7</b>	2.6	25.6
<i>Lobophyllia corymbosa</i>	0.0	<b>0.7</b>	2.6	28.2
<i>Leptoseris gardineri</i>	0.0	<b>0.7</b>	2.6	30.8
<i>Psammocora contigua</i>	0.0	<b>0.7</b>	2.4	33.2
<i>Echinopora gemmacea</i>	0.0	<b>0.7</b>	2.4	35.7
<i>Acropora kirstyae</i>	0.0	<b>0.7</b>	2.4	38.1
<i>Parascolymia vitiensis</i>	0.0	<b>0.7</b>	2.4	40.6
<i>Dipsastraea</i> cf. <i>speciosa</i>	<b>0.7</b>	0.0	2.4	43.0
<i>Pseudosiderastrea tayami</i>	<b>0.7</b>	0.0	2.4	45.4
<i>Montipora</i> sp.	0.4	1.0	2.4	47.7
<i>Merulina ampliata</i>	0.4	1.0	2.4	50.1

abundances of *Porites* spp. and *P. speciosa* were different although these were encountered at both sites, with the former being more abundant at EMB and the latter at JPB.

### 3.4. Sediment characteristics and geochemical signatures

Based on dominant grain size (Fig. 9), sites were classified as dominant mud facies (JPB\_12), high mud facies (EMB\_9) and coarse sand facies (EMB\_3, EMB\_6). Geochemical data showed that concentrations of Cd, Pb, and Zn were below their limit of detection, respectively <20 mg/kg, <30 mg/kg and <200 mg/kg (Table 3). The concentration of Cu was below or near to the limit of detection (<10 mg/kg). Mean metal concentrations ranked in the following decreasing order: Fe >> Ni ~ Cr > Co > Mn > Cu.

Fe accounted for 85–93% of the total concentration and reached 157.203 mg/kg on the Japanese Bank, a value of the same order of magnitude as on the slope of the embankment (EMB\_6: 104.390 mg·kg<sup>-1</sup>) but three times higher than in the flat and the bottom part of the embankment (EMB\_3: 33.207 mg·kg<sup>-1</sup>; EMB\_9: 50.265 mg·kg<sup>-1</sup>). The minimum value of 16.736 mg·kg<sup>-1</sup> was at the reference site MAA.

Similar patterns and ranking between JPB, EMB and MAA locations were found for all metals, with highest concentrations on JPB, intermediate concentrations on the slope of the embankment (EMB\_6), low concentrations on the flat (EMB\_3) and the bottom part of EMB (EMB\_9), and the lowest concentrations at the MAA reference site.

## 4. Discussion

A special issue of Marine Pollution Bulletin has been dedicated to New-Caledonia and more specifically to its southern lagoon (Vol. 61, Issues 7–12). New Caledonia has about a quarter of the world's known nickel resources. There are extensive open land-based mining extractions throughout the main island (Grande-Terre, Fig. 1). The raw minerals are either shipped abroad or processed locally. The oldest processing factory (since 1910) is located in Nouméa, Grande Rade. A surface area of 15 743 km<sup>2</sup> of reefs and lagoons has been listed as UNESCO World Heritage Areas in 2008 (Andréfouët and Wantiez, 2010), but the Heritage sites have been selected away from mining activities, and so are most of the MPAs. Elsewhere, environmental marine and land impact assessments have been required by law for all mining activities since 2009. However, the effects of mining activities on coral reefs remain scientifically poorly documented in New Caledonia,

particularly from reefs chronically subjected to anthropogenic and natural runoffs. Recent findings on the occurrences of coral diseases and lesions on reefs situated downstream of mining sites confirm that mining-induced sedimentation and turbidity are major threats to inshore reefs (Heintz et al., 2015). Runoffs have greatly increased the concentrations of heavy metals in the marine environment (Fichez et al., 2010) especially in the Grande Rade since the mining complex establishment (Dalto et al., 2006; Hédouin et al., 2010). The coral communities at the Japanese Bank, now with extensive rubble cover, have certainly suffered from such environmental change. The situation of the embankment is very different as it is an artificial substratum much more recently created (late 1990s). It is a purely artificial structure, with habitats entirely created by mining processing residue. The Embankment coral community settled under a relative high anthropogenic pressure. This may have induced a species selection and contributed to the among-sites community dissimilarity levels.

The Grande Rade Bay is the largest New Caledonia harbor with commercial trade and mining activities. The site is also subject to intense vessel traffic which may play a role in the resuspension and redeposition of metal-rich particle matter from the muddy bottom. This contributes to the turbidity conditions observed in the bay where *C. noumeae* corals were found in abundance. As such, the Grande-Rade cannot be considered as representative of a typical New Caledonian bay (Catala, 1958, 1964; Laboute, 1988; Borsa et al., 2009). However, the two study sites provide important cues on this endemic coral mushroom ecology as a metal and turbidity-tolerant species.

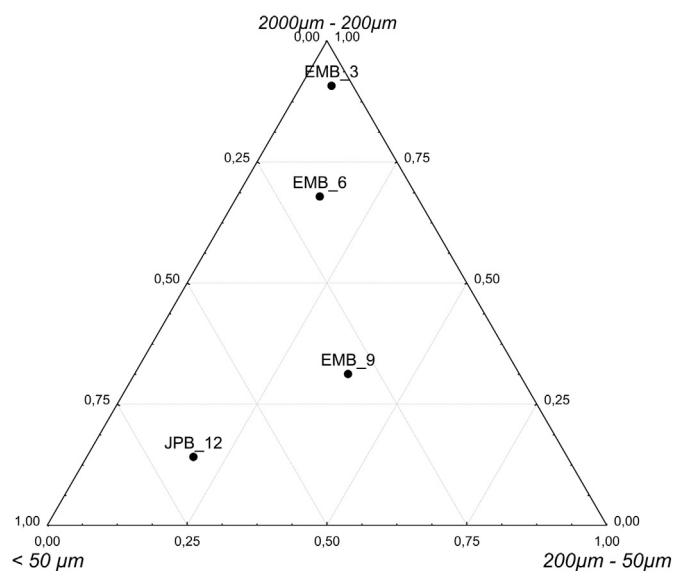
This first quantitative survey of the endemic and endangered mushroom coral species *C. noumeae* shows a mean density of up to 288 individuals per 50 m<sup>2</sup> on the natural Japanese Bank, with a high proportion (47%) of size class S (<1.5 cm Ø), representing new recruits. We measured colonies with Ø from less than 1.5 cm up to 6.5 cm, the largest size recorded thus far (Hoeksema and Borel Best, 1984). Large colonies were not well represented on the natural Japanese Bank, with 5% of the population. *C. noumeae* was also found at high densities on the man-made embankment which is only 2 km away from the Japanese Bank. The population there reaches an average of 82 colonies per 50 m<sup>2</sup>, with up to 178 colonies on the slope. Size structure of the population was relatively similar between the embankment sites, with a low fraction of juveniles. Hence, EMB seems to provide an adequate environment for the settlement of this species. However, *C. noumeae* densities at EMB were much lower than those at JPB and the proportions of juveniles were smaller. Regarding the other coral species found at EMB, although the overall coral abundance was similar between EMB and JPB, coral communities at the two sites had significantly different composition. This sum of observations suggests that the natural carbonate rubble at JPB is more suitable as habitat and for the settlement of *C. noumeae* and some other corals (e.g. branching and foliose growth forms) than the consolidated scoria at EMB. It also indicates that movements of the unconsolidated rubble and scoria, providing a hard substrate on the embankment slope, limit the recruitment and survival of *C. noumeae* but not the one of other species commonly encountered at EMB (notably the massive *Porites* and *Dipsastraea* spp.).

It cannot be excluded that some of the differences in coral community composition observed among sites could be partially related to the high patchiness observed, with several species being encountered only once

**Table 2**  
Between sites similarity percentage from SIMPER analyses.

	EMB_3	EMB_6	EMB_9	JPB
EMB_3	44.444			
EMB_6	52.587	71.795		
EMB_9	34.673	27.453	40	
JPB	16.833	29.297	15.641	53.83





**Fig. 9.** Triangular plot of superficial sediment granulometry of 3 classes sampled at each site. EMB\_3 = embankment 3 m depth; EMB\_6 = embankment 6 m depth; EMB\_9 = embankment 3 m depth; JPB\_12 = Japanese Bank 12 m depth.

at the same site or depth and with corals typically scattered and distant from each other. Less abundant species may have been de facto under-sampled. For example, *Pseudosiderastrea tayamai*, common at EMB but presently not recorded at JPB, has previously been collected at the latter site by one of the authors (IRD online database LagPlon: [http://lagplon.ird.nc/consultv2\\_5/rechSimple.faces](http://lagplon.ird.nc/consultv2_5/rechSimple.faces)).

The current lack of information on *C. noumeae* is limiting the ability to discuss a direct link between sizes and ages. However, age and size are directly related for many species of fungiids (Chadwick-Furman et al., 2000), and it can reasonably be assumed that the three size classes (small, medium, large) correspond to three different life stages (juvenile, adult and old). The high proportion of size S (juveniles), and the low density of size L (old individuals), suggest a high recruitment rate, and a high mortality rate as well, in the Grande-Rade harbor area.

Hydrodynamics of the Grand Rade has been well studied. Water circulation is driven by wind and tide (Jarrige et al., 1975; Morlière and Crémoux, 1981; Morlière, 1985; Ouillon et al., 2010). Depending on the tide, currents are alternatively directed into or outward the bay. Currents are relatively low with an average speed of 5 cm/s and a maximum of 15 cm/s. Local south-east trade winds create a general north-west drift (Douillet et al., 2001). The Japanese Bank and the embankment are only 2 km apart and their respective coral populations are likely connected by larval dispersal considering circulation in the bay. The Japanese Bank was probably one of the main initial sources from which coral propagules of *C. noumeae* arrived into the embankment and have continued to do so. However, despite a shared presence of *C. noumeae*, coral communities at the two sites differed significantly in overall composition and in the relative abundance of coral species. This suggests that while coral populations at JPB could be a source of

individuals for EMB, including *C. noumeae*, other species have actually reached the EMB from other sites with a different coral community composition.

Hydrodynamics is also a determinant factor of the sedimentation rate and the removal of materials. Sedimentation is high all along the EMB bay but there are differences in sediment granulometry between sites. Depth is another factor related to the differences between sites: depth influences wave-driven re-suspension and light attenuation, both critical for coral development (Fabricius, 2005). Sediments greatly influence the energetic balance of zooxanthellate corals (Riegl and Branch, 1995). It has been experimentally shown that this is partially due to the absorption or the reflection of light by the sediment, but also to the stimulation of mucus production. Corals constantly have to secrete mucus to protect themselves against fouling, desiccation and sedimentation (Wild et al., 2004). Decreased photosynthesis and mucus protection due to sedimentation shift the coral's energy balance. Moreover, sediments reduce heterotrophic energy gain by interfering with the prey capture capacity of the coral polyps and it has been shown that coral growth rates can be significantly reduced by sediment inputs (Prouty et al., 2014). Although the well-cited Roger's (1990) review suggests that a  $10 \text{ mg}\cdot\text{cm}^{-2}\cdot\text{d}^{-1}$  is a sediment threshold for coral survival, there is evidence from the Indo-Pacific region that many corals tolerate sedimentation levels more than 10 times this figure (Te, 2001). This is the case for corals in the naturally high sedimentary environments found in the bays and deep lagoon banks in New Caledonia where fleshy and large polyp species are abundant (Catala, 1958, 1964; Laboute, 1988; Borsa et al., 2009). The differences in coral communities measured between locations (EMB vs JPB) and between depths (EMB\_3; EMB\_6; EMB\_9) are probably driven by a combination of different factors including sediment quality and light availability (Fabricius, 2005; Erfteimeijer et al., 2012).

The Japanese Bank offers a suitable habitat for *C. noumeae*, with a high proportion of hard substrata made of dead coral skeletons in a muddy environment. Light intensity is relatively low even at shallow depths as sediment resuspension and sedimentation are high. This location is also characterized by high metal concentrations of Fe, Cr, Ni, and Mn, which are likely to be generated by the nearby nickel processing factory (Dalto et al., 2006). In contrast, the sediments at the reference Baie Maa contained lower metal concentrations. Many studies have focused on the effects of metals and sedimentation on corals (Reichelt-Brushett and Harrison, 1999, 2005; Gilmour, 2002; Fabricius, 2005; Reichelt-Brushett and Michalek-Wagner, 2005; Erfteimeijer et al., 2012). They underlined negative effects of metals on reproduction, recruitment and larval survival (Reichelt-Brushett and Harrison, 1999, 2005; Reichelt-Brushett and Michalek-Wagner, 2005) but also on growth and survival (Fabricius, 2005). Metals are known to affect coral metabolism and growth as enzymatic co-factors (Morel et al., 1994; Brown and Depledge, 1998). However, recent studies have also shown a positive effect of moderate metal concentrations on coral metabolism (Houlbrèque et al., 2012). The high abundances of *C. noumeae* reveal that this species tolerates or perhaps favors turbid metal-rich habitats. This species thrives in muddy areas and may have the ability to actively remove sediments, like other mushroom coral species (Bongaerts et al., 2012). A primary criterion to search for new

**Table 3**

Metal concentrations (mg/kg of dry matter) of superficial sediments sampled at each site. EMB\_3 = Embankment 3 m depth; EMB\_6 = Embankment 6 m depth; EMB\_9 = Embankment 3 m depth JPB\_12 = Japanese Bank 12 m depth; MAA = Control site.

	Cd (mg/kg)	Co (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
EMB_3	<20	61	518	16	33,207	400	1405	<30	<200
EMB_6	<20	248	7992	14	104,390	1945	3768	<30	<200
EMB_9	<20	174	3415	<10	50,265	781	4461	<30	<200
JAPB_12	<20	512	8239	<10	157,203	1967	6696	<30	<200
MAA	<20	14	181	<10	16,736	255	95	<30	<200

populations around New Caledonia is therefore to look for areas that are naturally impacted by soil erosion and mining. Surveys at additional sites will allow further investigations of the sedimentary context and metal concentrations in which *C. noumeae* occurs, and this species may help to understand its tolerance and adaptability to high sedimentation and metal concentrations. Overall, these first findings stress the need for further research on the ecology, population dynamic, and genetic of this endangered species, with the perspective to scientifically substantiate its conservation status.

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