



## Suspended particulate matter in Voh lagoon (New Caledonia): Impact of ultramafic rock mining on primary production<sup>☆,☆</sup>

Sandrine Chifflet<sup>a,\*</sup>, Jean-Louis Gonzalez<sup>b</sup>, David Varillon<sup>d</sup>, Anne Desnues<sup>d</sup>, Bernard Angeletti<sup>c</sup>, Adrien Duvivier<sup>c</sup>, Doriane Delanghe<sup>c</sup>, Cristèle Chevalier<sup>a</sup>

<sup>a</sup> Aix Marseille University, Université de Toulon, CNRS, IRD, MIO UM110, Marseille 13288, France

<sup>b</sup> IFREMER, LER PAC, Centre Méditerranée, Zone Portuaire de Brégaillon CS20 330, La Seyne-sur-Mer 83507, France

<sup>c</sup> Aix Marseille University, CNRS, IRD, Collège de France, INRAE, CEREGE, 13545 Aix-en-Provence Cedex 4, France

<sup>d</sup> Institut de Recherche pour le développement (IRD), UAR191 IMAGO, Nouméa 98848, New Caledonia

### ARTICLE INFO

#### Keywords:

Koniambo  
Metals  
Carbon  
Eutrophication  
Coastal ecosystem  
Particulate transport

### ABSTRACT

Open-pit mines are known to exacerbate soil erosion and generate large quantities of fine particles, which are carried by watersheds to coastal waters. In New Caledonia, the exploitation of ultramafic massifs highly enriched in metals (Co, Cr, Fe and Ni) can therefore have harmful effects on tropical lagoons by increasing turbidity and releasing toxic compounds to the marine food web. In this study, we used various biogeochemical (POC,  $\delta^{13}\text{C}$ , PON, POP, Chl *a*, Pheo *a*) and geochemical (Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sb, Sn, Ti, V, Zn) parameters to examine the origin, transport, and fate of suspended particulate matter (SPM) in the Voh lagoon after eight years of mining activities. Maximum concentrations of SPM ( $1.93 \text{ mg}\cdot\text{L}^{-1}$ ), Chl *a* ( $1.23 \text{ }\mu\text{g}\cdot\text{L}^{-1}$ ), Cr ( $327 \text{ }\mu\text{g}\cdot\text{g}^{-1}$ ), Co ( $32.4 \text{ }\mu\text{g}\cdot\text{g}^{-1}$ ) and Ni ( $756 \text{ }\mu\text{g}\cdot\text{g}^{-1}$ ) were observed in Vavouto bay, downstream of the Koniambo ultramafic massif. The increase in particle inputs linked to mining activity has led to the eutrophication of the lagoon. Due to transport processes, SPM are now distributed throughout the lagoon, settling at the bottom and burying the corals. In this context, the Voh lagoon presents a high ecological risk. This study provides an opportunity to refine predictive modelling techniques for contamination scenarios.

### 1. Introduction

Reef lagoons are among the most productive marine ecosystems and play a key role in influencing the genetic diversity of the oceans (Pérez-Ruzafa et al., 2019; Maggioni et al., 2021). Many marine species use them as nurseries and shelters (Adams and Ebersole, 2002). Furthermore, coral structures act as physical barriers against waves and ocean currents, thereby protecting the seabed and coastline from erosion (Elliff and Silva, 2017). However, reef lagoons are semi-closed ecosystems that rely on a delicate balance of inputs from both the land and the sea (Mentzel et al., 2023). Suspended particulate matter (SPM) consists of both allochthonous terrestrial particles and autochthonous biological particles (Mc Kergow et al., 2005; Bahadori et al., 2023; Chifflet et al., 2023). It is subject by various physical and biogeochemical processes including adsorption, complexation, dilution, flocculation and

degradation (Harmesa et al., 2024). In reef lagoons, the degradation of SPM is an important pathway for nutrient recycling, which has a strong influence on the biomass and metabolism of pelagic and benthic communities (Silveira et al., 2017; Lønborg et al., 2021; Pardo et al., 2023). Nevertheless, excessive SPM can lead to reef deterioration, either directly through burial processes or indirectly by inducing stress in corals due to strong light attenuation (Hoegh-Guldberg et al., 2017; 2019).

New Caledonia is part of the Melanesian archipelago, which is located in the southwest Pacific Ocean. The main island is large and mountainous ( $16\,500 \text{ km}^2$ ), surrounded by a long reef barrier ( $1\,600 \text{ km}$ ) which encloses a large tropical lagoon ( $24\,000 \text{ km}^2$ ) (Andréfouët et al., 2009). The New Caledonia archipelago has the third largest reef ecosystem in the world after the Australia's Great Barrier Reef and the Mesoamerican Barrier Reef. Due to their exceptional beauty,

<sup>☆</sup> For submission to Regional Studies in Marine Science

<sup>☆</sup> Impacts anthropiques, métaux, origine et devenir, transfert trophique

\* Corresponding author.

E-mail address: [sandrine.chifflet@mio.osupytheas.fr](mailto:sandrine.chifflet@mio.osupytheas.fr) (S. Chifflet).

biodiversity and unique geography, several marine areas have been classified as UNESCO World Heritage Sites (Payri et al., 2019). These landscapes were formed by the emergence of two parallel submarine ridges (Norfolk Ridge and Loyalty Ridge), resulting in complex geology comprising a mosaic of ultramafic and volcano-clastic sediments (Cluzel et al., 2001; Maurizot et al., 2020a,b). Following several million years of erosion and laterization, the ultramafic massifs became highly enriched in Fe (50–55 wt%), Mn (8–9 wt%), Cr (3–4 wt%), Ni (2.0–2.5 wt%) and Co (0.5–0.6 wt%) (Fandeur et al., 2009a,b; Dublet et al., 2012; 2017). In New Caledonia, these massifs form the highest mountains (up to 1 500 m) and cover one-third of the main island. They are subject to significant natural erosion due to heavy tropical precipitation and the dominance of weakly cohesive rocks (Chevillotte et al., 2006).

Since Jules Garnier discovered garnierite in 1867, New Caledonia has been one of the world's largest producers of Ni (Cluzel and Vigier, 2008). The ore is extracted using open-pit mining. This process produces large quantities of fine, metal-rich terrigenous particles that can easily be carried by wind and/or rain into neighbouring watersheds and lagoons (Losfeld et al., 2015; Boula et al., 2022). In the early 2000s, New Caledonia opened a mining site in the Koniambo ultramafic massif (KNS project), which included a pyrometallurgical plant that became fully operational in 2014. Various studies were carried out during the first four years of operation (2015–2019) to assess the environmental impact of mining activities. These examined the transport and properties of metals and metalloids (MM) across the Koniambo massif-lagoon continuum (Merrot et al., 2019, 2021; Boula et al., 2022), the mobility and bioavailability of MM in soils, plants, and river waters (Pasquet et al., 2016, 2018; Merrot et al., 2022), and variations in plankton communities in the neighbouring Voh lagoon (Pagano et al., 2025). The latter study showed that zooplankton abundance and diversity were negatively correlated with turbidity, and the authors observed that the Voh lagoon was being buried by large amounts of SPM.

Due to its small size and high reproduction rate, zooplankton is highly sensitive to human-induced pressures and is often used as a bioindicator of water quality (Serranito et al., 2016). In this context, the SELAMIK campaign was carried out in the Voh lagoon in March 2022 to reassess the fate of this ecosystem eight years after the start of mining

activities. The present study aimed to (1) examine the distribution patterns of particulate MM (Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sb, Sn, Ti, V, Zn), (2) analyse the relationships between particulate MM concentrations and mining activities, (3) quantify the contribution of SPM related to mining, and (4) assess the environmental risks.

## 2. Materials and methods

### 2.1. Study area and sampling

The Voh lagoon (164.5° – 164.7°E and 20.92° – 21.02°S; northwest of New Caledonia) covers approximately 100 km<sup>2</sup>, with 90% of the stations having a bathymetry of less than 20 m (Fig. 1, Table S1). The deepest stations are located around the Duroc channel (natural reef passage) extended by the KNS channel (artificial passage) leading to the Ni metallurgical port. A second natural reef passage (Pouanga channel) narrower and shallower is located to the northwest of the study area. The Voh lagoon is surrounded by the bays of Chasseloup, Vavouto and Pouaco. Chasseloup bay is located downstream of a volcano-sedimentary catchment area (also known as Voh plain), drained by the Témala river. By contrast, Vavouto bay receives SPM from the Tiéta, Foachianboué and Coco rivers (TFC rivers), crossing the Koniambo ultramafic massif (Audet, 2008; Maurizot et al., 2020a). In New Caledonia, lagoons are influenced by an uneven semi-diurnal tidal regime with a maximum amplitude of 1.6 m (Douillet, 1998).

The SELAMIK campaign was carried out between 03 and 14 March 2022 on board the French research vessel R/V *Alis*. The stations were sampled along two transects (northern transect: V16, V21, V27, V34, V31, V24, V16 and southern transect: V01, V09, V16, V15, V06, V07, V08, V09; in that chronological order) for two consecutive days and were repeated in 4 legs during the campaign to account for tidal variations (Fig. S1). In addition, mangrove stations (Pouaco, M35; Chasseloup, M24; Vavouto, M04) were sampled once using a rubber boat. In-situ parameters (depth, temperature, salinity, turbidity and fluorescence) were measured using a CTD probe (Seabird SBE 911plus) over the entire seawater column (surface to bottom) in the Voh lagoon and at a maximum depth of 50 m in the ocean (V01) or in the Duroc channel

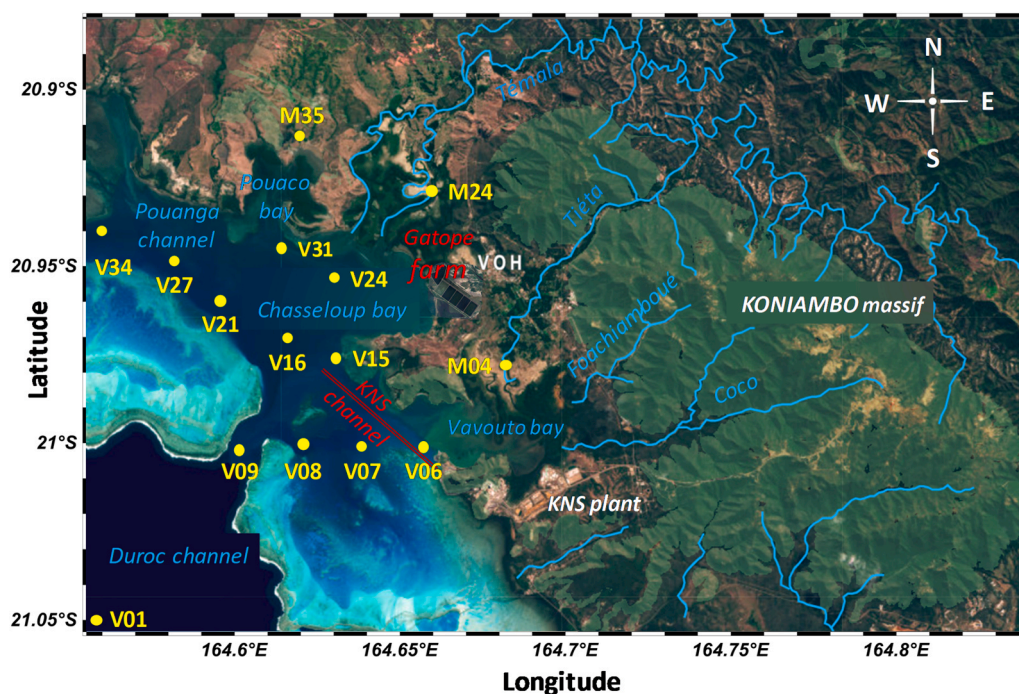


Fig. 1. Map of sampling sites showing topography and mining resources from Google Earth (<https://earth.google.com/web/>) and Georep (<https://dimenc.georep.nc>) databases, respectively.

(V09). Seawater samples were taken from the surface desalinated water (or at a depth of 5 m in the case of vertical salinity profiles) using a Niskin bottle for SPM, particulate organic carbon and its stable isotopes (POC and  $\delta^{13}\text{C}$ , respectively), particulate organic nitrogen and phosphorus (PON and POP, respectively), chlorophyll *a* and pheophytin *a* (Chl *a* and Pheo *a*, respectively) analyses. A NIO CZ bottle (metal-free bottle; Krachler and Shoty, 2009) was also used to collect samples at the same depth as the Niskin bottle for particulate MM (pMM) analyses.

SPM from the Niskin bottle were collected by low vacuum filtration ( $\sim 0.3$  bar) using glass fibre filters (Whatman GF/F, 0.7  $\mu\text{m}$  pore size) in different packaging: raw filters for Chl *a* and Pheo *a* analyses, calcinated filters (450°C, 6 h) for POC, PON, POP and  $\delta^{13}\text{C}$  analyses, and calcinated (105°C, 2 h) and pre-weighed filters for SPM determination. After the filtration, Chl *a* and Pheo *a* samples were transferred to micro-centrifuge tubes, POC, PON, POP and  $\delta^{13}\text{C}$  samples were transferred to calcinated (450°C, 6 h) aluminium foils and, SPM samples were transferred to Petri glass dishes after being rinsed with a few millilitres of ultrapure water to remove residual salts. SPM from NIO CZ bottle were collected by on-line filtration using pre-cleaned (bi-distilled HCl, 3%) cellulose ester filters (Millipore MCE, 0.2  $\mu\text{m}$  pore size) in accordance with GEOTRACES sampling practices (Aguilar-Islas et al., 2024). The upper valve of the NIO CZ bottle was connected to a bottle of argon gas (purity  $\geq 99.999\%$ ) by a perfluoroalkoxy (PFA) tube and slightly over-pressurized (+0.5 bar), while the lower valve was connected to a PFA filter holder (Savillex) placed on a container to collect the exact volume of filtered seawater. Filters were transferred to pre-cleaned (bi-distilled HCl, 1%) Analyslide Petri dishes (Pall Gelman) and sealed in two plastic bags. On board the R/V *Alis*, all samples were immediately stored at  $-20^\circ\text{C}$ . During the SELAMIK campaign, 3 blank filters were also prepared at regular intervals for each parameter.

## 2.2. Laboratory analyses

### 2.2.1. Suspended particulate matter

The SPM was determined in accordance with EN 872:2005 standard (AFNOR, 2005). Briefly, in the laboratory (SEDIM platform, CEREGE, Aix Marseille University), the SPM filters were dried overnight in an oven at  $60^\circ\text{C}$  then weighted after cooling (uncertainty  $\pm 5\%$ ).

### 2.2.2. Particulate organic carbon and nitrogen, carbon isotopic compositions

POC and PON concentrations and  $\delta^{13}\text{C}$  were measured simultaneously on the same sample in the LAMA platform (IRD Research Centre, New Caledonia). The samples were first decarbonated by contact with HCl vapours (12 h) to remove inorganic carbon, freeze-dried, punched (11 mm diameter), weighted and wrapped in tin capsules for analysis. PON, POC and  $\delta^{13}\text{C}$  measurements were carried out using elemental analyser mass spectrometer (Integra CN, Sercon). The  $\delta^{13}\text{C}$  values were expressed in ‰ and reported relative to conventional reference standard Vienna Pee Dee Belemnite (VPDB) as describe by Wilson et al. (2024). Analytical uncertainties were  $\pm 0.2$  mol.mol $^{-1}$  for COP/NOP and  $\pm 0.2\%$  for  $\delta^{13}\text{C}$ . The blank filters gave signal well below the detection limit and were considered negligible.

### 2.2.3. Particulate organic phosphorus

POP samples were analysed in the LAMA platform (IRD Research Centre, New Caledonia) as described by Pujo-Pay and Raimbault (1994). Briefly, POP samples were oxidised by wet oxidation at  $120^\circ\text{C}$  under alkaline buffered conditions composed of mixing of borax ( $\text{Na}_2[\text{B}_4\text{O}_5(\text{OH})_4] \cdot 8 \text{H}_2\text{O}$ ; analytical grade) and potassium peroxydisulfate ( $\text{K}_2\text{S}_2\text{O}_8$ ; analytical grade). The samples were autoclaved for 30 min in cleaned Pyrex bottles, cooled at laboratory temperature and analysed directly by colorimetry (Technicon Bran+Luebbe III; Aminot et al., 2009). The analytical uncertainty was  $\pm 0.007 \mu\text{M}$  and the blank filters were not detectable.

### 2.2.4. Chlorophyll *a* and pheophytin *a*

The Chl *a* and Pheo *a* concentrations were measured simultaneously on the same sample in the LAMA platform (IRD Research Centre, New Caledonia) as described by Le Bouteiller et al. (1992). Chlorophyll pigments were extracted in the dark (1 h,  $20^\circ\text{C}$ ) in methanol (95%, analytical grade) without grinding filters. The fluorescence of the extracts was measured using a Turner Designs fluorometer (TD700) before and after acidification (0.5 M HCl, analytical grade). The fluorometer was calibrated with a pure Chl *a* standard (C5753, Sigma-Aldrich) previously titrated by spectrophotometry (Neveux and de Billy, 1986). The analytical uncertainty was  $\pm 10\%$  with a limit of detection of  $\sim 0.05 \mu\text{g} \cdot \text{L}^{-1}$ . The blank filters were not detectable.

### 2.2.5. Particulate metals and metalloids

Particulate MM samples were conditioned in a clean room (ISO 5) at the 2METO platform (MIO, Aix Marseille University) using high-purity acids (bi-distilled HCl and  $\text{HNO}_3$ ; commercial HF, Fisher) and ultrapure water (Milli-Q Integral 3, Millipore). Prior the SELAMIK campaign, the MCE filters and Analyslide Petri dishes were pre-cleaned overnight in HCl bath (1%) then rinsed thoroughly with MilliQ according to GEOTRACES protocols (Twining et al., 2015; Aguilar-Islas et al., 2024). Each MCE filter was slipped into an Analyslide Petri dish, dried under a laminar hood (ISO 1), labelled, pre-weighed, and stored in two plastic bags. Following the SELAMIK campaign, filters were freeze-dried, weighed and digested on a hot plate ( $120^\circ\text{C}$ , 12 h) in closed PFA vials (Savillex) with an acid mixture ( $\text{HNO}_3$ , HCl, HF; 2/2/1 v/v) diluted to 50%. The acid mixture was then evaporated to near-dryness and the samples were re-dissolved with  $\text{HNO}_3$  (2%).

The analysis of pMM (Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sb, Sn, Ti, V, Zn) was carried out by mass spectrometry (ICP-MS NexION 300; Perkin Elmer) at the LA-ICP-MS platform (CEREGE, Aix Marseille University). Instrumental mass drifts and matrix interferences were corrected by adding an internal Rb standard on-line. Analytical blanks were below 1% of the signal and considered negligible. Quality controls were performed using a certified reference material (BCR 414, Commission of the European Communities). All results were within the satisfactory USEPA (1996) recommendations ( $100 \pm 10\%$ ) except for Mn and Pb (84%). Details of the control quality (blank, limit of detection, recovery) are presented in Table S2.

## 2.3. Risk assessment

### 2.3.1. Enrichment factor

The enrichment factor (EF) is widely used to assess metal inputs in coastal ecosystems (Salomons and Förstner, 1984). EF is expressed as follows:

$$EF = \frac{(M/X)_{SPM}}{(M/X)_{background}}$$

where M and X represent the concentrations of a target metal and a reference element in SPM and background (i.e., reference sample), respectively. Due to its high concentration in the mineral clays and its high ability to bind with organic compounds, Al is often used as a reference element (Windom et al., 1989; Din, 1992; Summers et al., 1996). However, there is no consensus, and other elements such as Fe (Breslin and Sañudo-Wilhelmy, 1999), Co (Matthai and Birch, 2001), Mn (Salmanighabeshi et al., 2015) or Sc (Popoola et al., 2023) are also used as reference depending on to the environmental context. In this study, Ti was found in volcano-clastic sediments, but not in laterites (Audet, 2008). Therefore, the latter was used as reference element to assess metal inputs from Koniambo ultramafic massif (Chifflet et al., 2026). The choice of background matrix is also often debated as this can introduce bias and lead to the over- or underestimation of anthropogenic inputs (Covelli, Fontonlan, 1997; Abraham and Parker, 2008; Varrica et al., 2024). A common approach is to use compiled data from the upper

continental crust (Wedepohl, 1995), regional natural sites if available (Wang et al., 2025) or data from sediment cores at pre-industrial levels. Therefore, the geochemical composition of the Voh plain, composed of volcano-clastic sediments, was used as the background matrix to calculate the metal enrichment related to the weathering of the Koniambo massif (Audet, 2008). EF greater than 1 indicate metal enrichment, classified as minor ( $1 < EF < 3$ ), moderate ( $3 < EF < 5$ ), moderate to severe ( $5 < EF < 10$ ), severe ( $10 < EF < 25$ ), very severe ( $25 < EF < 50$ ), and extremely severe enrichment ( $EF > 50$ ).

### 2.3.2. Toxic risk index

The mean Effects Range-Median Quotient (m-ERM-Q) is an integrated index used to assess ecological risk relative to the Effects Range-Median (ERM). The ERM level is defined as the MM concentrations at which adverse effects are frequently observed (Long et al., 1995).

$$m-ERM-Q = \frac{1}{n} \times \sum_{i=1}^n \frac{M_i}{ERM_i}$$

where M represents the concentrations of the target metal. ERM defined in the Sediment Quality Guidelines are for As =  $70 \mu\text{g}\cdot\text{g}^{-1}$ , Cd =  $9.6 \mu\text{g}\cdot\text{g}^{-1}$ , Cr =  $370 \mu\text{g}\cdot\text{g}^{-1}$ , Cu =  $270 \mu\text{g}\cdot\text{g}^{-1}$ , Ni =  $51.6 \mu\text{g}\cdot\text{g}^{-1}$ , Pb =  $218 \mu\text{g}\cdot\text{g}^{-1}$ , Sb =  $25 \mu\text{g}\cdot\text{g}^{-1}$  and Zn =  $124 \mu\text{g}\cdot\text{g}^{-1}$  (Long et al., 1995). The m-ERM-Q is classified as follows: m-ERM-Q  $< 0.1$ , low risk with 9% probability of toxicity;  $0.11 \leq m-ERM-Q < 0.5$ , moderate risk with 21% probability of toxicity;  $0.51 \leq m-ERM-Q < 1.5$ , high risk with a 49% probability of toxicity; and m-ERM-Q  $\geq 1.51$ , very high risk a 76% probability of toxicity.

The new Toxic Risk Index (TRI) is used to re-assess the toxic risk (Ranjbar et al., 2017):

$$TRI = \sum_{i=1}^n \sqrt{\frac{(M_i/TEL_i)^2 + (M_i/PEL_i)^2}{2}}$$

where M represents the concentrations of the target metal, TEL and PEL are the threshold and the probable effect levels, respectively. The two levels (TEL and PEL) were defined in Sediment Quality Guidelines from the monitoring of MM effects in fish, shellfish and sediment (MacDonald et al., 2000). MM concentrations below TEL (As =  $7.2 \mu\text{g}\cdot\text{g}^{-1}$ , Cd =  $0.7 \mu\text{g}\cdot\text{g}^{-1}$ , Cr =  $52.3 \mu\text{g}\cdot\text{g}^{-1}$ , Cu =  $18.7 \mu\text{g}\cdot\text{g}^{-1}$ , Ni =  $15.9 \mu\text{g}\cdot\text{g}^{-1}$ , Pb =  $30.2 \mu\text{g}\cdot\text{g}^{-1}$ , Zn =  $124 \mu\text{g}\cdot\text{g}^{-1}$ ) have no adverse effect on biota, while those above PEL (As =  $41.6 \mu\text{g}\cdot\text{g}^{-1}$ , Cd =  $4.2 \mu\text{g}\cdot\text{g}^{-1}$ , Cr =  $160 \mu\text{g}\cdot\text{g}^{-1}$ , Cu =  $108 \mu\text{g}\cdot\text{g}^{-1}$ , Ni =  $42.8 \mu\text{g}\cdot\text{g}^{-1}$ , Pb =  $112 \mu\text{g}\cdot\text{g}^{-1}$ , Zn =  $271 \mu\text{g}\cdot\text{g}^{-1}$ ) are likely to have adverse effect. The TRI is classified as follows: TRI  $\leq 5$ , no toxic risk;  $5 < TRI \leq 10$ , low toxic risk;  $10 < TRI \leq 15$ , moderate toxic risk;  $15 < TRI \leq 20$ , considerable toxic risk; and TRI  $> 20$ , very high toxic risk.

### 2.4. Statistical analyses

Statistical analyses were performed using Xlstat software package version 2025.1.0 (Addinsoft, <https://www.xlstat.com>). Spearman's rank correlation was used to examine the potential relationships between biogeochemical variables (SPM, COP,  $\delta^{13}\text{C}$ , NOP, POP, Chl *a*, Pheo *a*) and geochemical (pMM) variables. Next, Principal Component Analysis (PCA) was performed to reduce the number of biogeochemical and geochemical variables into two load factors in order to identify potential correlations between variables and sampling sites. All statistical tests were performed at a significance level of  $p < 0.05$ .

### 2.5. Source partitioning

Stable isotopes are widely used in geochemistry as tracer of mixing processes. For example, the proportions of 3 carbon sources in SPM can be assessed using the following mathematical model:

$$(\delta^{13}\text{C})_{SPM} = X_U (\delta^{13}\text{C})_U + X_V (\delta^{13}\text{C})_V + X_M (\delta^{13}\text{C})_M$$

$$(POC/Chl\ a)_{SPM} = X_U (POC/Chl\ a)_U + X_V (POC/Chl\ a)_V + X_M (POC/Chl\ a)_M$$

$$X_U + X_V + X_M = 1$$

where  $\delta^{13}\text{C}$  the  $^{13}\text{C}$  isotopic composition (‰), the POC/Chl *a* is the carbon ratio (g/g),  $X_U$ ,  $X_V$  and  $X_M$  are the relative contributions of ultra-mafic, volcano-sedimentary and marine sources in SPM, respectively.

## 3. Results

### 3.1. Physical parameters in Voh lagoon

The SELAMIK campaign was conducted during a period of heavy rainfall. Approximately 182 mm per month of precipitation has been recorded at the Koné weather station since December 2021, twice as much as the monthly average over the past 50 years (<https://www.met.ec.nc/nouvelle-caledonie/climat/relevés>). However, the weather was rather calm and dry during the campaign except at the beginning of Leg 4 with 11.9 mm of rain collected in 24 h (versus an annual average of 3 mm per day; Dutheil et al., 2020) and a westerly to north eastern wind shift (Fig. 2).

In situ-parameter (temperature, salinity, turbidity and fluorescence) are presented according to latitudinal and longitudinal (V24-V16-V09-V01 and V34-V27-V21-V16-V07-V06, respectively) transects in Leg 1 (Fig. 3) as well as in Leg 2, 3 and 4 (Fig. S2, S3 and S4, respectively). For all CTD casts, (legs and stations), the temperature varied from 25 to 31°C, the salinity ranged between 33.5 and 35.5 PSU, the turbidity was  $< 2$  NTU and the fluorescence  $< 1 \mu\text{g}\cdot\text{L}^{-1}$ . The highest turbidity and fluorescence values were observed in the bays of Chasseloup (V24) and Vavouto (V06), while the highest temperature and lowest salinity were observed in surface water (depth  $< 10$  m).

### 3.2. Biogeochemical tracers

The concentrations of biogeochemical parameters (SPM, POC,  $\delta^{13}\text{C}$ , PON, POP, Chl *a*, Pheo *a*) and the variability of discrete sampling in relation to weather and tidal conditions was assessed using statistical values (mean, standard deviation and coefficient of variation) on the 4 samples per station (Table 1). The detailed values are presented in Table S3. The highest values for SPM ( $2.93 \pm 0.73 \text{ mg}\cdot\text{L}^{-1}$ ), POC ( $29.0 \pm 7.60 \mu\text{M}$ ), PON ( $2.21 \pm 0.82 \mu\text{M}$ ), Chl *a* ( $1.23 \pm 0.57 \mu\text{g}\cdot\text{L}^{-1}$ ) and Pheo *a* ( $0.34 \pm 0.07 \mu\text{g}\cdot\text{L}^{-1}$ ) were observed in bay of Vavouto (V06) and, in front of the bay of Pouaco (V31) for POP ( $0.15 \pm 0.07 \mu\text{M}$ ). The lowest values were all observed in V01 (Ocean; SPM =  $0.40 \pm 0.31 \text{ mg}\cdot\text{L}^{-1}$ , COP =  $5.72 \pm 1.85 \mu\text{M}$ , NOP =  $0.69 \pm 0.29 \mu\text{M}$ , POP =  $0.90 \pm 0.02 \mu\text{M}$ , Chl *a* =  $0.24 \pm 0.09 \mu\text{g}\cdot\text{L}^{-1}$  and Pheo *a* =  $0.08 \pm 0.03 \mu\text{g}$ .

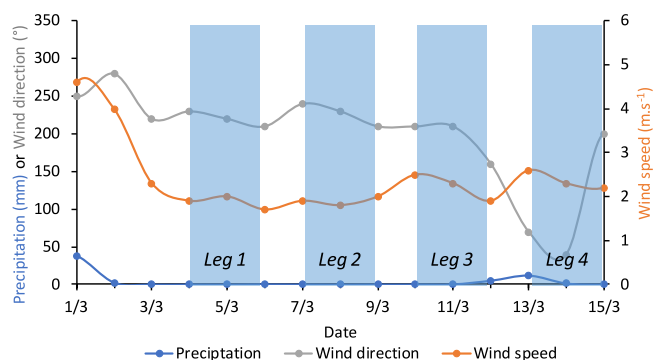


Fig. 2. Weather conditions (precipitation, wind speed and direction) between March 1 and 15, 2022.

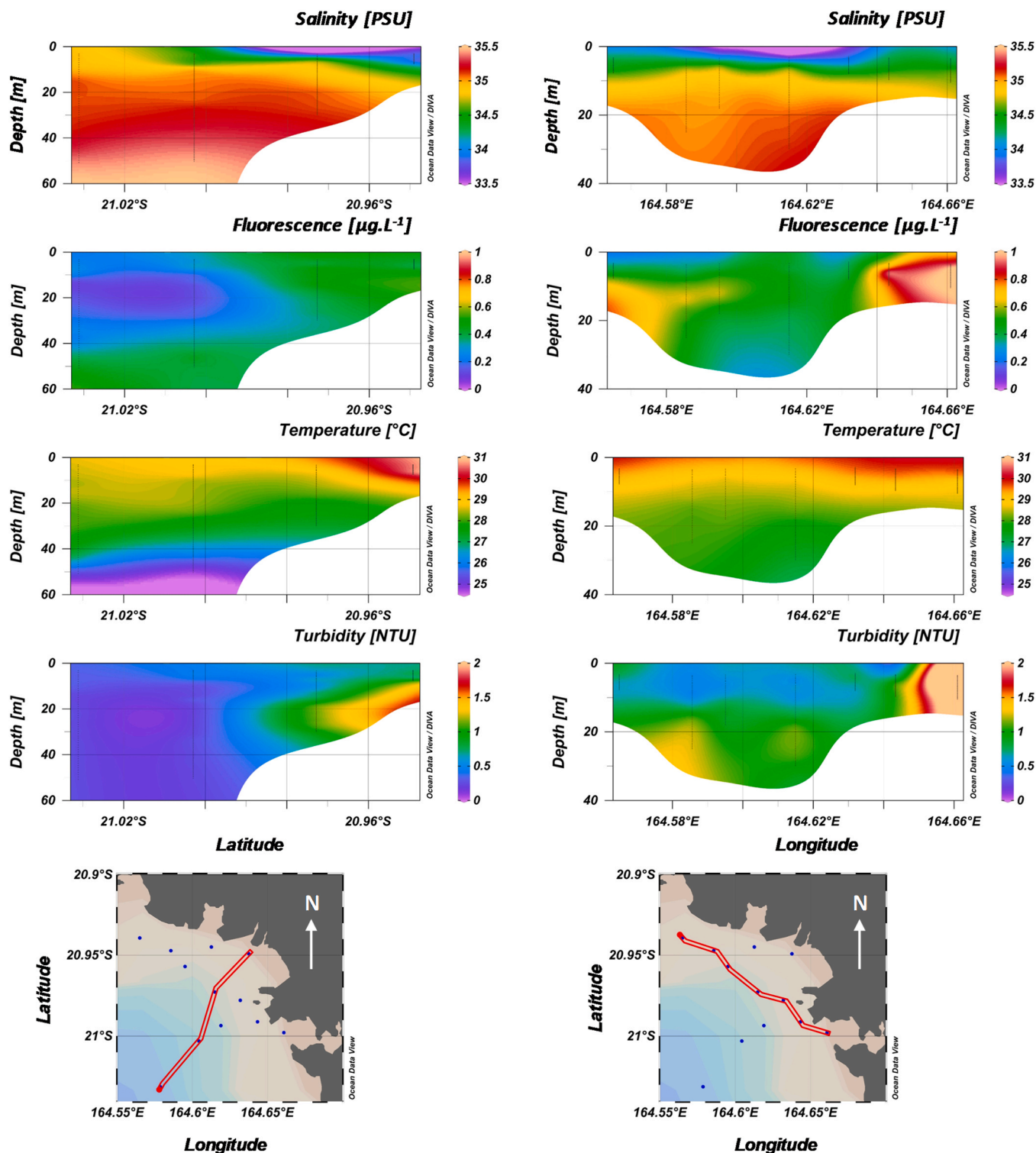


Fig. 3. Vertical profiles of salinity (PSU), fluorescence ( $\mu\text{g.L}^{-1}$ ) temperature ( $^{\circ}\text{C}$ ) and turbidity (NTU) during the Leg 1 (04–05 March 2022). Data are presented along latitudinal and longitudinal transects (V24-V16-V09-V01 and V34-V27-V21-V16-V07-V06, respectively) using Ocean Data View (ODV) software version 5.8.1 (<https://odv.awi.de>).

$\text{L}^{-1}$ ). Overall, biogeochemical parameters had a variability lower than 20% for all stations, with the exception of Chl *a*, which varied from 20% (V21, near reef) to 79% (V09; Duroc channel). Similarly, SPM showed wide variability up to 78% at V01 (Ocean).

### 3.3. Particulate MM concentrations

The mean pMM concentrations and sampling variability (standard deviation and coefficient of variation) are shown in Table 2 and detailed values in Table S4. The lowest pMM concentrations were found at V27 (near Pouanga channel) for Al ( $14.2 \pm 4.66 \text{ mg.g}^{-1}$ ), As ( $18.5 \pm 4.81 \text{ }\mu\text{g.g}^{-1}$ ), Co ( $6.91 \pm 0.77 \text{ }\mu\text{g.g}^{-1}$ ), Cr ( $77.7 \pm 23.9 \text{ }\mu\text{g.g}^{-1}$ ), Cu

**Table 1**

Biogeochemical data (SPM,  $\delta^{13}\text{C}$ , POC, PON, POP, Chl *a* and Pheo *a*) from surface waters ( $\leq 5$  m). Statistical values correspond to the mean, standard deviation (SD) and coefficient of variation (CV) of SPM collected on a spring-neap tide cycle. The mangroves stations (M04, M24, M35) were sampled once ( $n = 1$ ).

Station		SPM mg.L <sup>-1</sup>	$\delta^{13}\text{C}$ ‰	POC μM	PON μM	POP μM	Chl <i>a</i> μg.L <sup>-1</sup>	Pheo <i>a</i> μg.L <sup>-1</sup>
V01	Mean (n = 4)	0.40	-19.97	5.72	0.69	0.09	0.24	0.08
	SD	0.31	3.16	1.85	0.29	0.02	0.09	0.03
	CV (%)	78	16	32	42	20	37	42
V06	Mean (n = 4)	2.93	-11.51	29.0	2.21	0.10	1.23	0.34
	SD	0.73	2.28	7.60	0.82	0.01	0.57	0.07
	CV (%)	25	20	26	37	10	46	22
V07	Mean (n = 4)	1.01	-16.49	15.2	1.47	0.10	0.86	0.26
	SD	0.44	4.79	2.76	0.58	0.02	0.28	0.02
	CV (%)	44	29	18	39	17	33	7
V08	Mean (n = 4)	1.02	-19.01	11.8	1.30	0.10	0.80	0.25
	SD	0.30	3.22	2.52	0.46	0.02	0.34	0.07
	CV (%)	30	17	21	35	21	43	27
V09	Mean (n = 3)	0.55	-18.68	6.69	0.90	0.10	0.43	0.16
	SD	0.30	3.22	1.29	0.30	0.03	0.11	0.03
	CV (%)	54	17	19	33	26	25	21
V15	Mean (n = 4)	1.16	-18.98	11.3	1.44	0.10	0.62	0.18
	SD	0.42	3.12	0.81	0.23	0.03	0.14	0.04
	CV (%)	36	16	7	16	25	23	23
V16	Mean (n = 11)	0.85	-19.43	9.10	1.19	0.09	0.57	0.21
	SD	0.47	2.40	1.31	0.17	0.05	0.20	0.07
	CV (%)	56	12	14	15	55	36	32
V21	Mean (n = 4)	0.95	-18.45	7.88	1.06	0.11	0.53	0.19
	SD	0.50	2.87	2.15	0.37	0.03	0.10	0.03
	CV (%)	52	16	27	35	28	19	17
V24	Mean (n = 4)	0.80	-22.04	12.7	1.58	0.13	0.49	0.15
	SD	0.42	0.47	2.82	0.27	0.05	0.07	0.02
	CV (%)	52	2	22	17	42	15	17
V27	Mean (n = 4)	1.21	-18.15	9.42	1.21	0.09	0.53	0.19
	SD	0.47	3.12	1.59	0.37	0.01	0.11	0.03
	CV (%)	39	17	17	31	12	20	15
V31	Mean (n = 4)	1.04	-20.39	12.9	1.64	0.15	0.65	0.17
	SD	0.09	1.55	3.57	0.43	0.07	0.20	0.04
	CV (%)	9	8	28	26	49	30	21
V34	Mean (n = 4)	0.91	-17.01	10.6	1.24	0.11	0.49	0.16
	SD	0.48	3.89	2.10	0.29	0.02	0.09	0.03
	CV (%)	52	23	20	23	21	19	21
M04	(n = 1)	17.7	-27.49	44.1	4.62	0.24	1.06	0.44
M24	(n = 1)	9.21	-28.94	77.6	6.13	0.27	2.16	0.65
M35	(n = 1)	4.30	-20.32	40.4	3.94	0.37	1.86	0.50

SD: standard deviation

CV: coefficient of variation

( $48.1 \pm 49.8 \mu\text{g.g}^{-1}$ ), Fe ( $10.7 \pm 3.21 \text{ mg.g}^{-1}$ ), Mn ( $364 \pm 138 \mu\text{g.g}^{-1}$ ), Ni ( $118 \pm 19.5 \mu\text{g.g}^{-1}$ ), Ti ( $1.09 \pm 0.44 \text{ mg.g}^{-1}$ ), V ( $32.3 \pm 10.9 \mu\text{g.g}^{-1}$ ), and at V06 (Vavouto bay) for Cd ( $0.13 \pm 0.05 \mu\text{g.g}^{-1}$ ), Pb ( $3.67 \pm 2.53 \mu\text{g.g}^{-1}$ ), Sb ( $0.35 \pm 0.17 \mu\text{g.g}^{-1}$ ), Sn ( $2.20 \pm 0.99 \mu\text{g.g}^{-1}$ ), Zn ( $72.2 \pm 38.7 \mu\text{g.g}^{-1}$ ). The highest pMM concentrations were found at different stations depending on the target element: at V31 (in front of the bay of Pouaco) for Al ( $71.1 \pm 29.0 \text{ mg.g}^{-1}$ ), Fe ( $51.3 \pm 22.7 \text{ mg.g}^{-1}$ ), Mn ( $1102 \pm 290 \mu\text{g.g}^{-1}$ ), Ti ( $4.47 \pm 1.79 \text{ mg.g}^{-1}$ ) and V ( $136 \pm 53.3 \mu\text{g.g}^{-1}$ ); at V06 (Vavouto bay) for Co ( $32.4 \pm 21.8 \mu\text{g.g}^{-1}$ ), Cr ( $328 \pm 201 \mu\text{g.g}^{-1}$ ), and Ni ( $756 \pm 484 \mu\text{g.g}^{-1}$ ); at V01 (Ocean) for As ( $84.7 \pm 101 \mu\text{g.g}^{-1}$ ), Cd ( $1.47 \pm 1.48 \mu\text{g.g}^{-1}$ ), Cu ( $385 \pm 334 \mu\text{g.g}^{-1}$ ), and Sn ( $16.0 \pm 15.3 \mu\text{g.g}^{-1}$ ); at V09 (Duroc channel) for Sb ( $2.46 \pm 3.17 \mu\text{g.g}^{-1}$ ) and Zn ( $459 \pm 640 \mu\text{g.g}^{-1}$ ); at V24 (Chasseloup bay) for Pb ( $14.4 \pm 2.64 \mu\text{g.g}^{-1}$ ). In general, the variability of pMM concentrations was also station-dependent. The lowest variabilities (between 10% and 60%) were found in Chasseloup bay (V08, V15, V24, V24, V27, V31 and V34) for all elements except Cu and Sn where they were higher than this trend. The greatest variabilities (between 80% and 150%) were found in ocean or Duroc channel (V01 and V09, respectively) and intermediate variabilities (between 50% and 100%) were found along the longitudinal transect (V06-V07-V16-V21) for all elements.

## 4. Discussion

### 4.1. Suspended particulate matter transport in Voh lagoon

New Caledonia's climate is typical of the central and western Pacific. During the austral summer (November-April), rainfall can be abundant, increasing river flows by up to  $300 \text{ m}^3.\text{s}^{-1}$  (Faure et al., 2010). Extreme events such as tropical storms or cyclones trigger landslides and flash floods, promoting the transfer of SPM along the land-lagoon-ocean continuum (Dupouy et al., 2020; Sellier et al., 2021). In addition to this horizontal transport, water circulation in shallow lagoons is influenced by oceanic forcing such as swell in the channels, wave breaking on the reef and tidal currents, which may result in vertical resuspension of fine sediments. In the southwest lagoon of New Caledonia, the horizontal and vertical inputs of SPM can quickly triple during the austral summer (Clavier et al., 1995).

In this study, the highest fluorescence and turbidity values were observed with the lowest salinity values in the shallow waters of Vavouto and Chasseloup bays, highlighting the horizontal and vertical transfer of SPM from land to lagoon (Fig. 3, Fig S2-4). In addition to terrigenous transport, river discharges are often highly enriched in nutrients, which can lead to eutrophication in sheltered areas of New Caledonia's lagoons (Pinazo et al., 2004; Fichez et al., 2010). A previous study showed that the mangrove forest downstream the Témala and TFC rivers only offers partial protection to the Voh lagoon, filtering some of

**Table 2**

pMM concentrations (Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sb, Sn, Ti, V, Zn) from surface waters ( $\leq 5$  m). Statistical values correspond to the mean, standard deviation (SD) and coefficient of variation (CV) of SPM collected on a spring-neap tide cycle. The mangroves stations (M04, M24, M35) were sampled once ( $n = 1$ ).

Station	Al mg. g <sup>-1</sup>	As µg. g <sup>-1</sup>	Cd µg. g <sup>-1</sup>	Co µg. g <sup>-1</sup>	Cr µg. g <sup>-1</sup>	Cu µg. g <sup>-1</sup>	Fe mg. g <sup>-1</sup>	Mn µg. g <sup>-1</sup>	Ni µg. g <sup>-1</sup>	Pb µg. g <sup>-1</sup>	Sb µg. g <sup>-1</sup>	Sn µg. g <sup>-1</sup>	Ti mg. g <sup>-1</sup>	V µg. g <sup>-1</sup>	Zn µg. g <sup>-1</sup>
V01, Mean (n = 4)	16.3	84.7	1.47	16.4	259	385	15.0	486	283	7.57	1.27	16.0	2.37	49.9	290
SD	20.1	101	1.48	21.7	342	334	19.6	621	390	7.92	1.52	15.3	2.92	62.5	306
CV (%)	124	119	101	132	132	86.9	130	128	138	105	120	95.6	124	125	105
V06, Mean (n = 4)	32.3	23.8	0.13	32.4	328	66.2	37.0	461	756	3.67	0.35	2.20	2.33	75.1	72.2
SD	19.3	8.25	0.05	21.8	201	66.1	23.2	243	484	2.53	0.17	0.99	1.47	39.6	38.7
CV (%)	60	35	39	68	61	100	63	53	64	69	47	45	63	53	53
V07, Mean (n = 4)	28.4	24.8	0.19	25.8	277	72.8	30.2	469	617	6.28	0.54	4.24	1.98	66.8	99.2
SD	26.5	15.9	0.07	24.2	254	47.5	29.6	377	618	4.40	0.21	2.51	1.60	61.3	32.3
CV (%)	93	64	39	94	92	65	98	80	100	70	39	59	81	92	33
V08, Mean (n = 4)	15.9	17.6	0.21	10.5	125	87.0	13.7	322	225	4.74	0.38	5.55	1.20	34.7	80.0
SD	7.32	3.42	0.10	4.22	25.9	71.9	5.54	198	86.8	2.37	0.08	5.82	0.30	13.8	19.9
CV (%)	46	19	45	40	21	83	41	61	39	50	20	105	25	40	25
V09, Mean (n = 3)	35.2	77.3	1.02	24.9	266	219	29.1	738	465	11.2	2.46	38.5	3.5	81.9	459
SD	30.2	96.2	0.78	21.1	235	304	24.4	551	371	12.3	3.17	57.1	3.6	71.6	640
CV (%)	86	124	77	85	88	139	84	75	80	110	129	148	103	87	139
V15, Mean (n = 4)	24.3	23.6	0.28	15.5	153	60.5	20.4	556	323	5.27	0.37	6.40	1.63	52.0	87.2
SD	3.70	6.96	0.18	3.29	41.3	42.9	3.30	240	88.7	0.98	0.15	6.13	0.35	8.05	44.2
CV (%)	15	29	64	21	27	71	16	43	27	19	40	96	21	15	51
V16, Mean (n = 11)	25.1	34.1	0.46	15.8	161	243	20.3	689	299	6.78	0.83	10.9	1.91	55.6	123
SD	16.7	23.9	0.33	12.9	125	401	14.1	556	263	4.75	0.67	14.0	1.14	35.8	116
CV (%)	66	70	72	81	77	165	69	81	88	70	81	128	60	64	95
V21, Mean (n = 4)	26.3	25.7	0.68	11.8	121	80.6	18.9	708	194	6.53	0.72	7.98	2.09	54.9	142
SD	18.2	12.3	0.83	6.10	77.7	46.4	12.5	354	106	3.96	0.41	2.15	1.18	37.1	115
CV (%)	69	48	122	52	64	58	66	50	55	61	56	27	57	68	81
V24, Mean (n = 4)	69.7	48.1	0.30	24.6	235	236	46.7	1348	383	14.4	0.74	10.9	4.26	130	199
SD	7.86	14.6	0.12	4.08	47.4	120	5.54	384	66.4	2.64	0.16	8.47	0.59	17.8	73.8
CV (%)	11	30	40	17	20	51	12	29	17	18	22	78	14	14	37
V27, Mean (n = 4)	14.2	18.5	0.19	6.91	77.7	48.1	10.7	364	118	4.35	0.38	6.97	1.09	32.3	93.2
SD	4.66	4.81	0.13	0.77	23.9	49.8	3.21	138	19.5	1.80	0.24	4.00	0.44	10.9	60.9
CV (%)	33	26	66	11	31	104	30	38	16	41	64	57	41	34	65
V31, Mean (n = 4)	71.1	42.1	0.15	25.7	244	189	51.3	1102	389	13.7	0.76	7.29	4.57	136	156
SD	29.0	12.3	0.05	11.2	112	140	22.7	290	191	6.03	0.43	4.61	1.79	53.3	49.0
CV (%)	4	29	34	43	46	74	44	26	49	44	56	63	39	39	32
V34, Mean (n = 4)	28.1	30.9	0.44	13.0	130	189	21.3	682	200	6.69	0.55	8.83	2.25	60.6	106
SD	9.65	10.8	0.29	5.03	47.5	223	6.83	341	74.5	2.77	0.28	7.89	1.06	19.2	42.6
CV (%)	34	35	65	39	36	118	32	50	37	41	50	89	47	32	40
M04 (n = 1)	40.6	7.04	0.03	31.8	282	27.5	39.9	603	658	8.98	0.64	2.56	2.67	72.3	239
M24 (n = 1)	81.4	24.9	0.01	30.1	365	58.6	60.2	688	523	19.7	1.31	8.59	4.96	145	165
M35 (n = 1)	74.0	27.6	0.23	34.5	309	58.1	61.7	1287	416	16.9	0.82	4.20	5.48	163	144

SD: standard deviation

CV: coefficient of variation

the mineral and organic compounds (POC, MM, nutrients) transported by these rivers (Noël et al., 2015). Finally, the Gatope shrimp farm located behind the Chasseloup mangrove also disrupts the biogeochemical balance of this bay (Aimé et al., 2018). Indeed, New

Caledonia's aquaculture farms release untreated wastewaters that has a high organic matter content, resulting in a significant increase in nutrient inputs in the shoreline (David et al., 2010) and thus, potential risks of eutrophication and hyper-sedimentation in the vicinity of the

Gatope shrimp farm (Molnar et al., 2013).

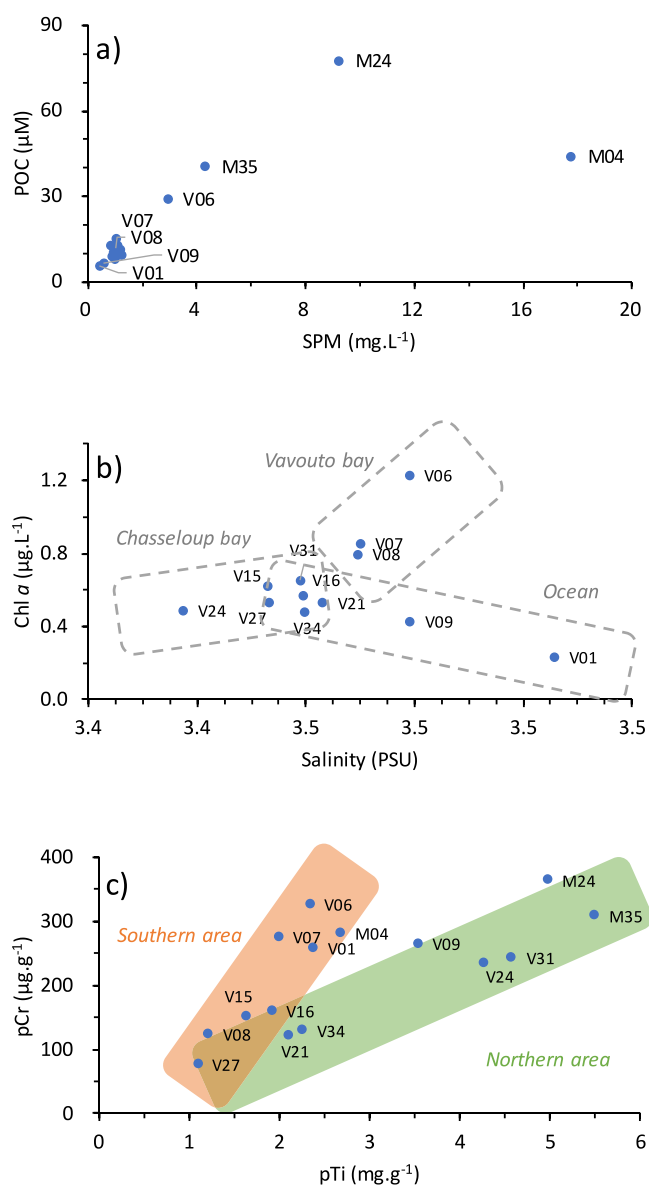
#### 4.2. Potential effects on primary production dynamic

In this context, POC in the lagoon would be driven by dominant allochthonous terrestrial inputs (from mangrove plant detritus, freshwater plankton, volcano-clastic and ultramafic sediments, etc.) and secondary autochthonous marine sources (from microalgae, phytoplankton, zooplankton, seagrasses, etc.). Previous studies in New Caledonia have shown that the marine plankton communities are influenced by natural forcing, such as hydrodynamic and climatic events. For example, variability in phytoplankton communities is linked to allochthonous inputs in Ouano lagoon (Rodier et al., 2024) and, rainfall in the Voh-Koné region increases the Chl *a* concentrations and disrupts zooplankton communities (Pagano et al., 2025). As expected, biogeochemical and pMM concentrations show non-conservative behaviours in our study (Fig. 4). The pMM source in Vavouto mangrove (M04) is markedly different that of Chasseloup and Pouaco mangroves (M24 and

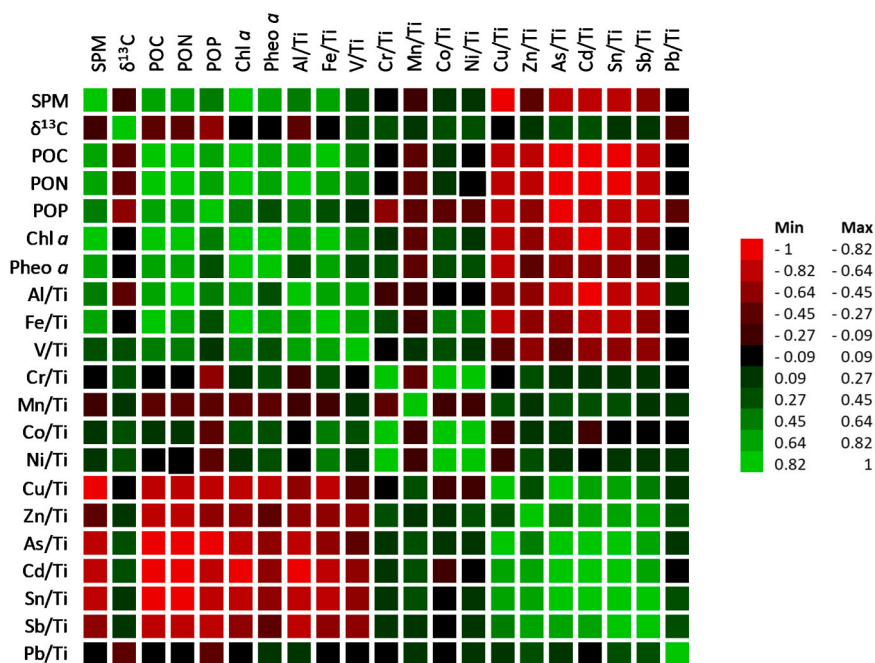
M35, respectively). In addition, variations of Chl *a* concentrations relative to the salinity gradient highlight distinct planktonic characteristics depending on the geographical area, with stations possibly influenced by the catchment areas of Vavouto bay (V06, V07, V08), Chasseloup bay (V15, V24, V27 and V31) and the ocean (V01, V09, V21 and V34).

The dynamics of SPM and the transfer of pMM to the lagoon are influenced by the weathering of volcano-sedimentary and ultramafic soils. Feldspars are the dominant minerals in the Earth's crust and lead to the formation of kaolinite, an aluminosilicate clay mineral which has a strong affinity for hydrated metal ions (Doi et al., 2020). These are formed from a wide range of magmas, with Al being the main constituent of granite and gabbro. The weathering of ultramafic soils also leads to the accumulation of residual Al in sediments. However, the mineral composition of the Koniambo massifs does not contain Ti (Audet, 2008). Consequently, normalising the samples by pTi concentrations could highlight pMM concentrations from the Koniambo ultramafic massif. The Spearman's correlation matrix shows that the biogeochemical parameters (SPM, POC, PON, POP, Chl *a* and Pheo *a*) are strongly positively correlated with Al/Ti and Fe/Ti ( $r > 0.7$ ,  $p < 0.05$ ), and negatively correlated with As/Ti, Cd/Ti, Cu/Ti, Sb/Ti, Sn/Ti and Zn/Ti ( $r < -0.7$ ,  $p < 0.05$ ) (Fig. 5; Table S5). Additionally, strong positive correlations are observed between Co/Ti, Cr/Ti, and Ni/Ti ( $r > 0.9$ ,  $p < 0.05$ ). Runoff from ultramafic rocks is generally enriched in pCo, pCr and pNi notably by incorporation into the crystalline structures of Fe-(oxyhydr) oxides, Mn-oxides and phyllosilicates (Fandeur et al., 2009a; Dublet et al., 2012; Butt and Cluzel, 2013). However, the latter exhibit non-conservative behaviour in Voh lagoon (Fig. 4c; Fig. S5). This pattern appears to be influenced by the watersheds with different terrigenous sources in the southern (V06, M04) and northern (M24, M35) zones.

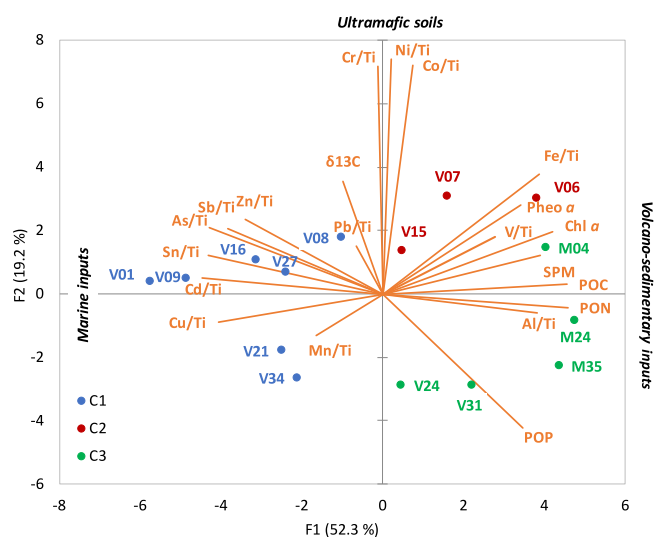
Elucidating the dynamics of SPM is challenging, as Voh lagoon appears to be characterised by two gradients: a turbidity gradient along the land-lagoon-ocean continuum (latitudinal transect), and a primary production gradient parallel to the coast (longitudinal transect). Indeed, the highest pMM concentrations are observed near the shoreline in Vavouto and Chasseloup bays. However, Chl *a* concentrations are twice as high in Vavouto bay than in Chasseloup bay. Consequently, autochthonous primary production seems to be closely associated with allochthonous terrigenous inputs. Statistical analysis (PCA-HCA) is used to explore similarities and hidden patterns among samples, particularly when the relationships between the variables (biogeochemical parameters and pMM) and the observations (stations) are unclear (Fig. 6; Fig. S6). The first two load factors (F1 and F2) explain 71.5% of the cumulative variance ( $p < 0.05$ ), with F1 showing high positive loads ( $> 0.82$ ) for biogeochemical parameters (SPM, POC, PON, Chl *a*) as well as Al/Ti, and high negative loads ( $< -0.82$ ) for As/Ti, Cd/Ti, Cu/Ti, Sb/Ti and Sn/Ti. The second axis (F2) shows strong positive loads ( $> 0.93$ ) for Co/Ti, Cr/Ti, Ni/Ti and  $\delta^{13}\text{C}$ . Based on the above discussion, the normalisation by Ti emphasises the pMM from the ultramafic Koniambo massif. Elements such as Co, Cr, and Ni are highly enriched in laterites (Fandeur et al., 2009a; Dublet et al., 2012; Butt and Cluzel, 2013). Therefore, the positive charges on F2 could indicate terrigenous inputs from the Koniambo massif. Taking this into account, the F1 axis indicates that primary production is mainly influenced by non-ultramafic inputs. The elemental composition of mafic/volcanic rocks is dominated by Al, Ca, Si, Fe, K, Mg, and Na, which can be used as indicators of terrigenous input (Larson et al., 2015). Therefore, the positive loads of Al/Ti and Fe/Ti, as well as Chl *a* and Pheo *a*, on F1 could suggest that primary production is favoured by allochthonous volcano-clastic sediments. Conversely, the increase in negative loads for the other studied elements (As, Cd, Cu, Sb, Sn and Zn) on F1 does not appear to be the result of terrigenous sources. It may instead be due to autochthonous marine inputs. Hierarchical clustering analysis is used to group stations with similar characteristics. Dendrogram analysis reveals three distinct groups of stations: C1 comprises oceanic or near reef stations (V01, V08,



**Fig. 4.** Relationships between biogeochemical and geochemical concentrations in SPM from surface waters ( $\leq 5$  m): a) POC vs SPM, b) Chl *a* vs Salinity and, c) pCr vs pTi. Values are averaged from samples collected on a spring-neap tide cycle ( $n = 4$ ).



**Fig. 5.** Spearman correlation matrix plot for biogeochemical parameters (SPM,  $\delta^{13}\text{C}$ , POC, PON, POP, Chl *a* and Pheo *a*), and normalised pMM concentrations by pTi in surface waters ( $\leq 5$  m). Statistical analysis was performed using the average of the data collected on a spring–neap tide cycle ( $n = 4$ ).



**Fig. 6.** Statistical analyses (PCA-HCA) of biogeochemical parameters and pMM concentrations normalised to Ti in F1-F2 plan (XLstat software version 2024.4.2, Addinsoft). Statistical analysis was performed using the average of the data collected on a spring–neap tide cycle ( $n = 4$ ). Principal Component Analysis (PCA) was performed using Spearman's correlation with a probability  $p < 0.05$  (variables in orange) and Hierarchical Clustering Analysis (HCA) was performed using Ward's method with squared Euclidean distances (clusters C1, C2 and C3 in blue, red and green dots, respectively).

V09, V16, V21, V27 and V34); C2 comprises stations in Vavouto bay or the KNS channel (V06, V07 and V15); and C3 comprises mangrove and Chasseloup bay stations (M04, M24, M35, V24 and V31) (Fig. S7). Accordingly, the PCA-HCA analysis reveals the following: stations in C1 are influenced by marine inputs; those in C2 by the weathering of mafic and volcanic soils; and those in C3 by terrestrial inputs mainly from the weathering of volcano-clastic sediments.

### 4.3. Assessment of source mixing and spatial distribution

During their transport through the land-lagoon-ocean continuum, SPM are transformed by numerous physical, chemical and biological processes such as scavenging or resuspension, adsorption or desorption, ingestion or excretion, etc. (Caneul and Hardison, 2016). Biogeochemical ratios (POC/PON, POC/Chl *a*) and carbon isotopic composition ( $\delta^{13}\text{C}$ ) are useful tools for characterising the quality and origin of SPM due to its high carbon content. Indeed, the POC/Chl *a* ratio is generally used to distinguish living phytoplankton ( $\sim 50\text{--}150\text{ g.g}^{-1}$ ) from detrital SPM ( $< 200\text{ g.g}^{-1}$ ) or other terrigenous material ( $> 200\text{ g.g}^{-1}$ ; Ferchiche et al., 2024). The POC/PON ratio is also applied to characterise phytoplankton ( $\sim 6\text{ mol.mol}^{-1}$ ) and terrestrial material ( $> 12\text{ mol.mol}^{-1}$ ); Bianchi and Bauer, (2011)). However, these ratios (POC/Chl *a* and POC/PON) are not conservative and can be modified by various biotic (microbial degradation, growth rate) and abiotic (e.g., fixation of ammonium in clay mineral lattice) processes, thus weakening the difference between the marine and terrestrial origin of SPM. Due to the complexity of the latter,  $\delta^{13}\text{C}$  can be used as a more specific and sensitive carbon source fingerprint, with the  $\delta^{13}\text{C}$  of terrigenous matter and marine phytoplankton being lower and higher than  $-25\%$ , respectively. Consequently, the relative contribution of allochthonous terrestrial and autochthonous marine SPM in coastal ecosystem can be estimated with greater accuracy by combining the biogeochemical ratios (POC/PON or POC/Chl *a*) with carbon isotopic composition ( $\delta^{13}\text{C}$ ) in mixing diagrams.

In this study, POC/PON ratios have the lowest values near channels and the reef barrier (C/N  $\sim 7.5\text{ mol.mol}^{-1}$ ; V09, V15, V16, V21, V27 and V31). The highest values are observed in mangroves and Vavouto bay (C/N  $> 10.0\text{ mol.mol}^{-1}$ ; M04, M24, M35 and V06). These results are in agreement with other studies carried out in Saint Vincent and La Conception bays (New Caledonia, southwest lagoon), and demonstrate that coastal SPM is essentially a mixture of terrestrial material from mangroves and marine plankton (Marchand et al., 2011; Debenay et al., 2015). The POC/Chl *a* values range from  $\sim 170\text{--}470\text{ g.g}^{-1}$  (V08-V21 to M04-M24, respectively) suggesting a mix of autochthonous marine sources and allochthonous terrestrial inputs. The Fig. 7 (POC/Chl *a* vs  $\delta^{13}\text{C}$ ) highlights the mixing of sources by pointing out three

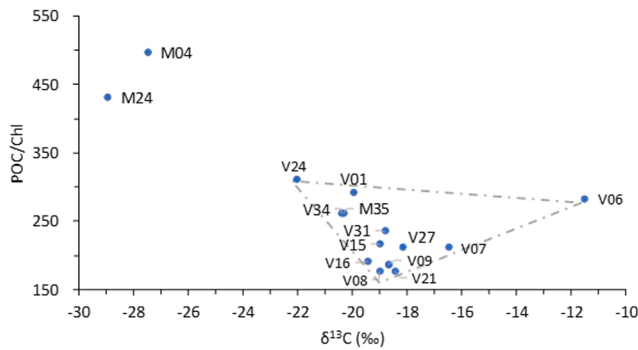


Fig. 7. Relationships between POC/Chl *vs*  $\delta^{13}\text{C}$ . Values are averaged from samples collected in surface waters ( $\leq 5$  m) on a spring-neap tide cycle ( $n = 4$ ).

end-members: 1) V06, 2) M04-M24, and 3) V08-V09-V21. The  $\delta^{13}\text{C}$  vary between  $-11.51\text{‰}$  (V06) and  $-28.94\text{‰}$  (M24) with V08-V09-V21 at  $-18.7\text{‰}$ . In the southwest lagoon of New Caledonia, the most  $^{13}\text{C}$ -depleted sources are found in rivers (SPM,  $-28.0\text{‰}$ ) or in leaves of mangroves (*Avicenia marina*,  $-27.3\text{‰}$  and *Rhizophora stylosa*,  $-30.2\text{‰}$ ; Briand et al., 2015) whereas a  $^{13}\text{C}$  enrichment is found in marine primary producers and consumers (diatoms  $-25.1\text{‰} \pm 0.8\text{‰}$  or cyanophycean  $-17.9\text{‰} \pm 2.1\text{‰}$ ; Deborde et al., 2015 and zooplankton  $-19.3 \pm 0.8\text{‰}$ , Carassou et al., 2008). The most  $^{13}\text{C}$ -enriched sources are found in algal turfs ( $-17.87$  to  $-7.54\text{‰}$ ; Briand et al., 2015) and in the Koniambo ultramafic rocks ( $-15.3\text{‰}$  and  $-9.1\text{‰}$ ; Quesnel et al., 2016). However, in shallow mangroves, vertical mixing (*i.e.*, sedimentation and resuspension) is promoted by repeated tidal cycles, which increase biotic and abiotic transformations of SPM (Marchand et al., 2011).

Riverine SPM tends to be more  $^{13}\text{C}$ -depleted than marine end member, partly due to carbon kinetic fractionation during diagenesis processes (Bianchi and Bauer, 2011). In addition, mangroves are also weather sensitive, meaning that a single sample may not be used to accurately represent the source of  $\delta^{13}\text{C}$ . In this context, only data from coastal stations (V01 to V34) sampled during a spring-neap tidal cycle (mean value,  $n = 4$ ) were used to assess the mixing of carbon sources in Voh lagoon.

Based on the above discussion, V08-V09-V21 suggest the marine end member, V06 downstream of the TFC rivers could be the end member receiving runoff from ultramafic Koniambo massif and, V24 downstream of the Témala river could be the end member receiving runoff from volcano-clastic sediments. In this study, the biogeochemical composition of marine source ( $\delta^{13}\text{C}_{\text{M}}$  and  $\text{POC}/\text{Chl}_{\text{M}}$ ) is defined at the intercept between regression lines V24-V08 and V06-V21. The results show that SPM at station V24 circulates primarily within in Chasseloup bay (V31: 34%; V15: 25%; V16 and V27:  $\sim 15\%$ ), with a significant proportion found in the Pouanga channel (V34: 60%) and exported outside the lagoon (V01: 60%) (Fig. 8; Table S6). Similarly, SPM at station V06 is found in the Vavouto bay-Ocean continuum (V07: 34% - V09: 11% - V01: 17%) as well as in Chasseloup bay (V27: 17%; V31: 16%). These findings are consistent with the lagoon's hydrodynamics (Pagano et al., 2025). On average, during a tidal cycle, the incoming flow passes over the reef, while the outgoing flow passes through the Duroc channel. Taking these considerations into account, SPM from the Témala river is transported along a land-ocean continuum, whereas SPM from the TFC rivers enriches the waters of the Voh lagoon. Today, despite efforts over the past 20 years to implement environmental regulations and promote sustainable mining practices, the Voh lagoon is covered in silt and the coral in reef is dying. However, due to high concentrations of Chl *a* in mangroves and river mouths, the Voh lagoon

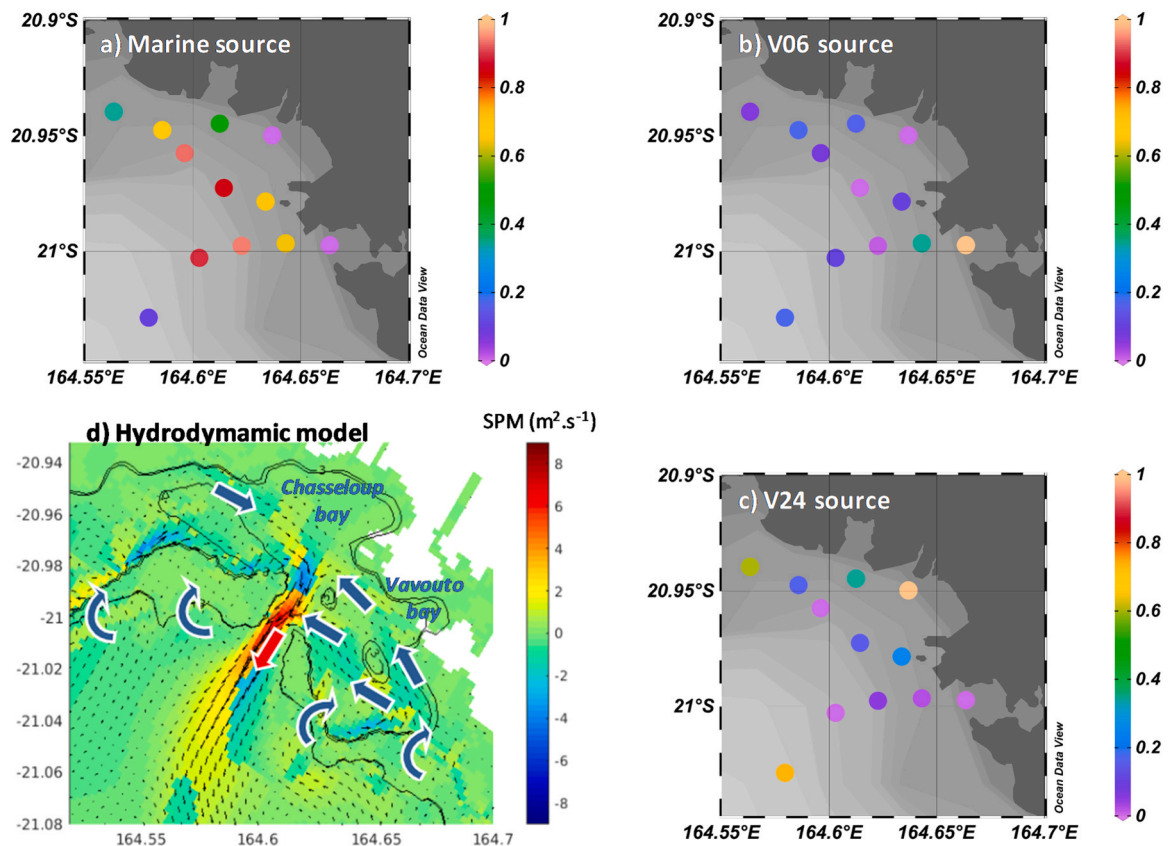


Fig. 8. Partitioning of SPM from a) marine, b) V06, and c) V24 sources expressed in relative abundance. Figures are presented using Ocean Data View software version 5.8.1 (<https://odv.awi.de>). Simulation of SPM transport (d) during a spring-neap tide cycle using CROCO 3D hydrodynamic model (from Pagano et al# 2025).

may remain a nursery area where juveniles manta rays and hammerhead shark were observed during the SELAMIK campaign. (Fig. 9)

#### 4.4. Estimation of ecological risks

Various indices of chemical contamination or ecological risk are used to assess the impact of MM on marine ecosystems. The EF values in the SPM of Voh lagoon indicate minor or no enrichment for Al, Co, Fe, Mn and V ( $EF < 3$ ), moderate to severe enrichment for Cr, Cu and Zn ( $3 < EF < 10$ ), and severe to very severe enrichment for Ni ( $10 < EF < 25$ ) (Table 3). The highest EF values for Cr and Ni are found near Vavouto bay (M04, V06, V07 and V15), which could typically result from the weathering of laterite soils. In contrast, the highest EF values for Cu and Zn are found near the Duroc channel (V01 and V09, respectively) and Chasseloup bay (V16, V24 and V34). This could suggest either low mangrove capture or an input from a marine source. Overall, mangroves act as a buffer zone between land and coastal areas. This results in high concentrations of metals in both sediments and plants (Lee et al., 2014). In New Caledonia, the transfer of Cr and Ni in mangrove forests is low due to their chemical speciation in stable oxide and sulphide complexes, as well as the physiological parameters of the root system that limit their transfer to the leaves (Marchand et al., 2012, 2016). Conversely, Cu and Zn are more mobile in mangroves plants and exhibit high bio-concentration, probably due to their metabolic activity and their ability to form complexes with organic matter. Consequently, the enrichment of Cu and Zn in SPM would likely be promoted by oceanic inputs.

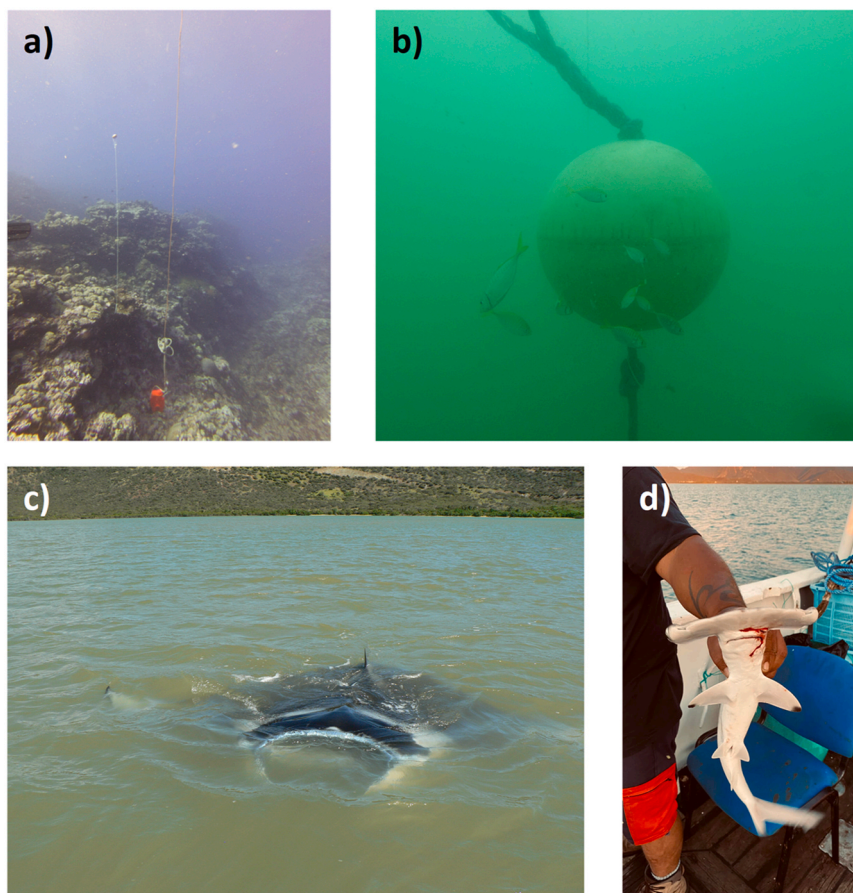
These metals (Cu, Cr, Ni and Zn) are used in various metabolic processes, depending on their chemical speciation. However, the latter can also have toxic effects on the marine food web (Wang, 2002; Morel et al., 2003). Cu and Zn play a key role in the formation of superoxide

dismutase, a bio-molecule reducing the oxidative damage (Ruan et al., 2020). In high concentration, primary producers (bacteria, archaea and eukaryotes) secrete organic ligands that form complexes with Cu, rendering it unavailable to other organisms (Corcoll et al., 2019). In addition, Zn are easily replaced by Cd or Co, which can induce cellular damage (Johns et al., 2023). In marine ecosystems,  $Cr^{VI}$  is highly reactive with nucleic acids and proteins, resulting in oxidative stress and impaired metabolic function (Ni et al., 2020). Ni plays a key role in the hydrolysis of urea to produce ammonium and carbamate, both of which are essential nutrients for primary production. (Morel et al., 2003). However, high Ni concentrations can reduce the fecundity of copepods and increase naupliar mortality Mohammed and Wang, (2010).

Overall, the integrated indexes (m-ERM-Q and TRI) suggest that the Voh lagoon poses a high ecological risk, with Vavouto bay (V06 and V07) presenting a higher risk than the area near the reef barrier (V21, V27) (Table 4). However, these indexes primarily utilise field data from American or Australian programmes in both freshwater and marine environments (McCready et al., 2006; Birch and Olmos, 2008). Their scope is limited by the absence of geochemical references at a local scale (Kosnik et al., 2022; Ogwu et al., 2025). Furthermore, the latter are based on experimental data using biological indicators and ignore the abundance and diversity of local species that can adapt to a wide range of metal concentrations (Yu et al., 2011). Therefore, appropriate biological studies are necessary to reduce uncertainties related to the assessment of ecotoxicological impact.

#### 5. Conclusion

The SELAMIK campaign aims to evaluate the origin and transport of SPM in surface waters using biogeochemical (POC,  $\delta^{13}C$ , PON, POP, Chl



**Fig. 9.** Pictures from Voh lagoon during the SELAMIK campaign: a) dead coral in the reef, (b) lagoon with very turbid water, (c) manta ray and d) juvenile hammerhead shark (during the SELAMIK campaign, 3 sharks were captured then released). Photo credit: David Varillon, Jean-Louis Gonzalez, Sandrine Chifflet.

**Table 3**

Values of enrichment factor (EF) in the SPM. EF was calculated using Ti as reference element, and volcano-clastic sediments of the Voh plain as background reference. Some elements such as Sb were not present or were below the detection limit (As, Cd, Pb and Sn) in the volcano-clastic sediments (Audet, 2008).

	Al	As	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Sb	Sn	V	Zn
V01	0.8			1.4	4.0	15.2	0.7	1.2	15.5				0.6	13.7
V06	1.7			2.9	5.1	2.7	1.7	1.2	42.1				0.9	3.5
V07	1.8			2.7	5.1	3.4	1.7	1.4	40.4				1.0	5.6
V08	1.6			1.8	3.8	6.7	1.2	1.6	24.2				0.8	7.4
V09	1.2			1.5	2.7	5.8	0.9	1.2	17.1				0.7	14.6
V15	1.8			2.0	3.4	3.5	1.4	2.0	25.7				0.9	6.0
V16	1.6			1.7	3.1	11.9	1.2	2.1	20.4				0.8	7.2
V21	1.5			1.2	2.1	3.6	1.0	2.0	12.0				0.7	7.6
V24	2.0			1.2	2.0	5.2	1.2	1.9	11.7				0.9	5.2
V27	1.6			1.3	2.6	4.1	1.1	2.0	14.1				0.8	9.6
V31	1.9			1.2	1.9	3.9	1.2	1.4	11.1				0.8	3.8
V34	1.5			1.2	2.1	7.9	1.0	1.8	11.5				0.8	5.3
M04	1.9			2.5	3.8	1.0	1.6	1.3	32.0				0.8	10.0
M24	2.0			1.3	2.7	1.1	1.3	0.8	13.7				0.8	3.7
M35	1.7			1.3	2.0	1.0	1.2	1.4	9.9				0.8	2.9

Moderate enrichment ( $3 < EF < 5$ )

Moderate to severe enrichment ( $5 < EF < 10$ )

Severe enrichment ( $10 < EF < 25$ )

Very severe ( $25 < EF < 50$ )

**Table 4**

Values of ecological risk indices (m-ERM-Q and TRI) per stations and their classification.

	m-ERM-Q	TRI
V01	1.2	44
V06	2.0	46
V07	1.7	39
V08	0.7	18
V09	1.6	46
V15	0.9	23
V16	1.0	31
V21	0.7	18
V24	1.3	37
V27	0.4	11
V31	1.2	35
V34	0.7	23
M24	1.5	36
M04	1.8	39
M35	1.3	31

m-ERM-Q < 0.1, low risk; 0.11–0.5, moderate risk; 0.51–1.5, high risk;  $\geq 1.51$ , very high risk

TRI  $\leq 5$ , no toxic risk; 5–10, low toxic risk; 10–15, moderate toxic risk; 15–20, considerable toxic risk;  $> 20$ , very high toxic risk.

*a*, Pheo *a*) and geochemical (Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sb, Sn, Ti, V, Zn) tracers to investigate the impact of Koniambo mining on the fate of the Voh lagoon after 8 years of operation. The SPM are composed of terrigenous material from the runoff of the Koniambo ultramafic massif in the southern zone (Vavouto bay) and the leaching from volcano-clastic rocks in the northern zone (Chasseloup bay) as well as marine primary production. In the lagoon, the fate of SPM is also influenced by hydrodynamics. The SPM of the Voh plain accumulates in the shallow waters of Chasseloup bay before being exported to the ocean through the Pouanga and Duroc channels. Conversely, the SPM from the runoff waters of the Koniambo ultramafic massif enters the Vavouto bay and is transported towards the Chasseloup bay by cross currents. However, the Voh lagoon is now completely buried due to the large influx of SPM.

While Ni mining is the driving force behind the New Caledonia's economy, it is also recognised as a major environmental concern. Although the price of Ni is extremely volatile due to competition from Asian countries, demand is steadily increasing due to the boom in low-carbon technologies. Therefore, the mining industry will face challenges to increase productivity, reduce costs and minimise environmental impact. This study revealed that weathering of lateritic soils increases

marine primary production due to their high nutrient and metal content. To accurately assess the impact of contaminants (MMs and other biogeochemical compounds) on marine communities and local populations, ecotoxicological studies should use machine learning and predictive modelling techniques to forecast contamination scenarios based on local historical data. This approach could improve the scientific rigour of assessments and encourage stakeholders to engage in environmental decision-making.

#### CRedit authorship contribution statement

**Cristèle Chevalier:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Doriane Delanghe:** Data curation. **Adrien Duvivier:** Formal analysis. **Bernard Angeletti:** Validation, Resources, Formal analysis. **CHIFFLET Sandrine:** Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **Anne Desnues:** Formal analysis. **David Varillon:** Validation, Data curation. **Jean-Louis Gonzalez:** Writing – review & editing, Validation, Methodology.

#### Funding

The project did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgments

The SELAMIK campaign was organized and supported by the French Oceanographic Fleet, CNRS/INSU, IFREMER and IRD. We are grateful to the “Centre IRD de Nouméa” (New Caledonia) for providing facilities. We especially thank the IRD/UAR191 IMAGO technical staff for their help with field sampling, and P. Gérard and L. Jamet for their logistical support in preparing the SELAMIK campaign and biogeochemical analyses. The project which led to this publication was supported by European Funds (FEDER, project 1166–39417) and from Excellence Initiative of Aix-Marseille University – A\*MIDEX, a French “Investissements d’Avenir” program. We also thank the platforms and technical

staff of the MIO. The project received additional funding from the MIO's "Action Sud" incentive program (LIM project). The authors would like to express their deepest gratitude to the anonymous reviewers for their constructive and insightful comments, which improved the original manuscript.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.risma.2026.104888](https://doi.org/10.1016/j.risma.2026.104888).

## Data availability

Data will be made available on request.

## References

- Abraham, G.M.S., Parker, R.J., 2008. Assessment of heavy metal enrichment factors and the degree of contamination in marine sediments from Tamaki Estuary, Auckland, New Zealand. *Environ. Monit. Assess.* 136, 227–238. <https://doi.org/10.1007/s10661-007-9678-2>.
- Adams, A.J., Ebersole, J.P., 2002. Use of back-reef and lagoon habitats by coral reef fishes. *Mar. Ecol. Prog. Ser.* 228, 213–226. (<https://www.jstor.org/stable/4865040>).
- AFNOR, E.N., 2005. Method by filtration through glass fibre filters. *Water Qual. Determ. suspended Solids* 872, 14.
- Aguliar-Islas, A., Bridgestock, L., Bundy, R., Conway, T., Hayes, C., Heimbürger, L.E., Planquette, H., Shaked, Y., 2024. Sampling and sample-handling protocols for GEOTRACES cruises. *GEOTRACES Community Pract. Version 4*, 153 (pp. & Appendices).
- Aimé, J., Allenbach, M., Bourgeois, C., Léopold, A., Jacotot, A., Vinh, T.V., Nho, N.T., Della Patrona, L., Marchand, C., 2018. Variability of CO<sub>2</sub> emissions during the rearing cycle of a semi-intensive shrimp farm in a mangrove coastal zone (New Caledonia). *Mar. Pollut. Bull.* 129, 194–206. <https://doi.org/10.1016/j.marpolbul.2018.02.025>.
- Aminot, A., Kérouel, R., Coverly, S., 2009. Nutrients in seawater using segmented flow analysis. In: Wurl, O. (Ed.), *Practical guidelines for the analysis of seawater*. CRC Press, p. 408p. ISBN 978-2-7592-0023-8.
- Andréfouët, S., Cabioch, G., Flammand, B., Pelletier, B., 2009. A reappraisal of the diversity of geomorphological and genetic processes of New Caledonian coral reefs: a synthesis from optical remote sensing, coring and acoustic multibeam observations. *Coral Reefs* 28, 691–707. <https://doi.org/10.1007/s00338-009-0503-y>.
- Audet, M.A., 2008. Le massif de Koniambo – Nouvelle Calédonie: formation et obduction d'un complexe ophiolitique de type SSZ. *Enrichissement en nickel, cobalt et scandium dans les profils résiduels*. Sci. De la Terre Univ. é De. Nouv. Cal. édonie 2008. NNT: 2008NICAL0021. (French language).
- Bahadori, M., Chen, C., Lewis, S., Wang, J., Shen, J., Hou, E., Rashti, M.R., Huang, Q., Bainbridge, Z., Stevens, T., 2023. The origin of suspended particulate matter in the Great Barrier Reef (article). *Nat. Commun.* 14 (1), 5629. <https://doi.org/10.1038/s41467-023-41183-z>.
- Bianchi, T.S., Bauer, J.E., 2011. Particulate organic carbon cycling and transformation. In: Wolanski, E., McLusky, D.S. (Eds.), *Treatise on Estuarine and Coastal Science*, 5. Waltham: Academic Press, pp. 69–117. <https://doi.org/10.1016/B978-0-12-374711-2.00503-9>.
- Birch, G.F., Olmos, M.A., 2008. Sediment-bound heavy metals as indicators of human influence and biological risk in coastal water bodies. *ICES J. Mar. Sci.* 65, 1407–1413. <https://doi.org/10.1093/icesjms/fsn139>.
- Boula, A., Laporte-Magoni, C., Gunkel-Grillon, P., Bour, O., Selmaoui-Folcher, N., 2022. Potential contamination of stream waters by ultramafic mining sediments: identification of geochemical makers (New Caledonia). *J. Geochem. Explor.* 232, 106879. <https://doi.org/10.1016/j.jgexplo.2021.106879>.
- Breslin, V.T., Sañudo-Wilhelmy, S.A., 1999. High spatial resolution sampling of metals in the sediment and water column in Port Jefferson Harbor, New York. *Estuaries* 22, 669–680. <https://doi.org/10.2307/1353054>.
- Briand, M.J., Bonnet, X., Goiran, C., Guillou, G., Letourneur, Y., 2015. Major Sources of Organic Matter in a Complex Coral Reef Lagoon: Identification from Isotopic Signatures ( $\delta^{13}C$  and  $\delta^{15}N$ ). *PLoS ONE* 10 (7), e0131555. <https://doi.org/10.1371/journal.pone.0131555>.
- Butt, C.R.M., Cluzel, D., 2013. Nickel Laterite Ore Deposits: Weathered Serpentinities. *Elements* 9, 123–128. <https://doi.org/10.2113/gselements.9.2.123>.
- Canuel, A., Hardison, A.K., 2016. Sources, ages, and alteration of organic matter in estuaries. *Annu. Rev. Mar. Sci.* 8, 409–434. <https://doi.org/10.1146/annurev-marine-122414-034058>.
- Carassou, L., Kulbicki, M., Nicola, T.J.R., Polunin, N.V.C., 2008. Assessment of fish trophic status and relationships by stable isotope data in the coral reef lagoon of New Caledonia, southwest Pacific. *Aquat. Living Resour.* 21, 1–12. <https://doi.org/10.1051/alr:2008017>.
- Chevillotte, V., Chardon, D., Beauvais, A., Maurizot, P., Colin, F., 2006. Long-term tropical morphogenesis of New Caledonia (Southwest Pacific): importance of positive epeirogeny and climate change. *Geomorphology* 81, 361–375. <https://doi.org/10.1016/j.geomorph.2006.04.020>.
- Chifflet, S., Briant, N., Tesán-Onrubia, J.A., Zaaboub, N., Amri, S., radakovitch, O., Bănanu, D., Tedetti, M., 2023. Distribution and accumulation of metals and metalloids in planktonic food webs of the Mediterranean Sea (MERITE-HIPPOCAMPE campaign). *Mar. Pollut. Bull.* 186, 114384. <https://doi.org/10.1016/j.marpolbul.2022.114384>.
- Chifflet, S., Gonzalez, J.L., Delanghe, D., Angeletti, B., Zambardini, T., Souhaut, M., van Beek, P., Chevalier, C., 2026. Erosion of an ultramafic massif: impact of geochemistry and sedimentary deposits in tropical lagoons in New Caledonia (in press). *Environ. Sci. Pollut. Res.* <https://doi.org/10.1007/s11356-025-37168-8>.
- Clavier, J., Chardy, P., Chevillon, C., 1995. Sedimentation of particulate matter in the South-West Lagoon of New Caledonia: spatial and temporal patterns. *Estuar. Coast. Shelf Sci.* 40, 281–294. [https://doi.org/10.1016/S0272-7714\(05\)80011-3](https://doi.org/10.1016/S0272-7714(05)80011-3).
- Cluzel, D., Vigier, B., 2008. Syntectonic mobility of supergene nickel ores of New Caledonia (Southwest Pacific). Evidence from garnierite veins and faulted regolith. *Resour. Geol.* 58, 161–170. <https://doi.org/10.1111/j.1751-3928.2008.00053.x>.
- Cluzel, D., Aitchison, J.C., Picard, C., 2001. Tectonic accretion and underplating of mafic terranes in the Late Eocene intraoceanic fore-arc of New Caledonia (Southwest Pacific): geodynamic implications. *Technophysics* 340, 23–59. [https://doi.org/10.1016/S0040-1951\(01\)00148-2](https://doi.org/10.1016/S0040-1951(01)00148-2).
- Corcoll, N., Yang, J., Backhaus, T., Zhang, X., Eriksson, K.M., 2019. Copper affects composition and functioning of microbial communities in marine biofilms at environmentally relevant concentrations. *Front. Microbiol.* 9, 3248. <https://doi.org/10.3389/fmicb.2018.03248>.
- Covelli, S., Fontonlan, G., 1997. Application of a normalisation procedure in determining regional geochemical baselines. *Environ. Geol.* 30, 34–45. <https://doi.org/10.1007/s002540050130>.
- David, G., Leopold, M., Dumas, P.S., Ferraris, J., Herrenschmidt, Fontenelle, G., 2010. Integrated coastal zone management perspectives to ensure the sustainability of coral reefs in New Caledonia. *Mar. Pollut. Bull.* 61, 323–334. <https://doi.org/10.1016/j.marpolbul.2010.06.020>.
- Debenay, J.P., Marchand, C., Molnar, N., Aschenbroich, A., Meziane, T., 2015. Foraminiferal assemblages as bioindicators to assess potential pollution in mangroves used as a natural biofilter for shrimp farm effluents (New Caledonia). *Mar. Pollut. Bull.* 93, 103–120. <https://doi.org/10.1016/j.marpolbul.2015.02.009>.
- Deborde, J., Marchand, C., Molnar, N., Patrona, L.D., Meziane, T., 2015. Concentrations and fractionation of carbon, iron, sulfur, nitrogen and phosphorus in mangrove sediments along an intertidal gradient (semi-arid climate, New Caledonia). *J. Mar. Sci. Eng. S*, 3, 52–72. <https://doi.org/10.3390/jmse3010052>.
- Din, Z.B., 1992. Use of aluminum to normalize heavy metal data from estuarine and coastal sediments of straits of Melaka. *Mar. Pollut. Bull.* 24, 484–491. [https://doi.org/10.1016/0025-326X\(92\)90472-1](https://doi.org/10.1016/0025-326X(92)90472-1).
- Doi, A., Khosravi, M., Ejtemaei, M., Nguyen, T.A.H., Nguyen, A.V., 2020. Specificity and affinity of multivalent ions adsorption to kaolinite surface. *Appl. Clay Sci.* 190, 105557. <https://doi.org/10.1016/j.clay.2020.105557>.
- Douillet, P., 1998. Tidal dynamics of the south-west lagoon of New Caledonia: observations and 2D numerical modelling. *Oceanol. Acta* 21, 69–79. [https://doi.org/10.1016/S0399-1784\(98\)80050-9](https://doi.org/10.1016/S0399-1784(98)80050-9).
- Dublet, G., Juillot, F., Morin, G., Fritsch, E., Fandeur, D., Ona-Nguema, G., Brown, G.E., 2012. Ni speciation in a New Caledonian lateritic regolith: a quantitative X-ray absorption spectroscopy investigation. *Geochim. Cosmochim. Acta* 95, 119–133. <https://doi.org/10.1016/j.gca.2012.07.030>.
- Dublet, G., Juillot, F., Brest, J., Noël, V., Fritsch, E., Proux, O., Olivi, L., Ploquin, F., Morin, G., 2017. Vertical changes of the Co and Mn speciation along a lateritic regolith developed on peridotites (New Caledonia). *Geochim. Cosmochim. Acta* 217, 1–15. <https://doi.org/10.1016/j.gca.2017.07.010>.
- Dupouy, C., Röttgers, R., Tedetti, M., Frouin, R., Lantoiné, F., Rodier, M., Martias, C., Goutx, M., 2020. Impact of contrasted weather conditions on CDOM Absorption/Fluorescence and biogeochemistry in the eastern lagoon of New Caledonia. *Front. Earth Sci.* 8, 54. <https://doi.org/10.3389/feart.2020.00054>.
- Dutheil, C., Menkes, C., Lengaigme, M., Vialard, J., Peltier, A., Bador, M., Petit, X., 2020. Fine-scale rainfall over New Caledonia under climate change. *Clim. Dyn.* 56, 87–108. <https://doi.org/10.1007/s00382-020-05467-0>.
- Elliott, C.I., Silva, I., 2017. Coral reefs as the first line of defense: Shoreline protection in face of climate change. *Mar. Environ. Res.* 127, 148–154. <https://doi.org/10.1016/j.marenvres.2017.03.007>.
- Fandeur, D., Juillot, F., Morin, G., Olivi, L., Cognigni, A., Ambrosi, J.P., Guyot, F., Fritsch, E., 2009a. Synchrotron-based speciation of chromium in an Oxisol from New Caledonia: importance of secondary Fe-(oxyhydr)oxides. *Am. Mineral.* 94, 710–719. <https://doi.org/10.2138/am.2009.3073>.
- Fandeur, D., Juillot, F., Morin, G., Olivi, L., Cognigni, A., Webb, S.M., Ambrosi, J.P., Fritsch, E., Guyot, F., Brown Jr, G.E., 2009b. XANES evidence for oxidation of Cr (III) to Cr (VI) by Mn-oxides in a lateritic regolith developed on Serpentinized ultramafic rocks of New Caledonia. *Environ. Sci. Technol.* 43, 7384–7390. <https://doi.org/10.1021/es900498r>.
- Faure, V., Pinazo, C., Torrèton, J.P., Douillet, P., 2010. Modelling the spatial and temporal variability of the SW lagoon of New Caledonia II: Realistic 3D simulations compared with in situ data. *Mar. Pollut. Bull.* 61, 480–502. <https://doi.org/10.1016/j.marpolbul.2010.06.040>.
- Ferchiche, F., Liénart, C., Charlier, K., Coynel, A., Gorse-Labadie, L., Savoye, N., 2024. Quantifying particulate organic matter: source composition and fluxes at the river-estuary interface. *Front. Freshw. Sci.* 2, 1437431. <https://doi.org/10.3389/ffwsc.2024.1437431>.
- Fichez, R., Chifflet, S., Douillet, P., Gérard, P., Gutierrez, F., Jouan, A., Ouillon, S., Grenz, C., 2010. Biogeochemical typology and temporal variability of lagoon waters in a coral reef ecosystem subject to terrigenous and anthropogenic inputs (New

- Caledonia). *Mar. Pollut. Bull.* 61, 309–322. <https://doi.org/10.1016/j.marpolbul.2010.06.021>.
- Harmesa, H., Wahyudi, A.J., Wong, K.H., Ikhsani, I.Y., 2024. The behaviour of particulate trace metals in marine systems: A review. *Mar. Environ. Res.* 202, 106729. <https://doi.org/10.1016/j.marenvres.2024.106729>.
- Hoegh-Guldberg, O., Poloczanska, E.S., Skirving, W., Dove, S., 2017. Coral Reef Ecosystems under Climate Change and Ocean Acidification (article). *Front. Mar. Sci.* 4, 158. <https://doi.org/10.3389/fmars.2017.00158>.
- Hoegh-Guldberg, O., Pendleton, L., Kaup, A., 2019. People and the changing nature of coral reefs. *Reg. Stud. Mar. Sci.* 30, 100699. <https://doi.org/10.1016/j.rsm.2019.100699>.
- Johns, C.E., Gattu, M., Camilli, S., Desaraju, A., Kolliputi, N., Galam, L., 2023. The Cd/Zn Axis: Emerging Concepts in Cellular Fate and Cytotoxicity. *Biomol* 13, 316. <https://doi.org/10.3390/biom13020316>.
- Kosnik, M.B., Hauschild, M.Z., Fantke, P., 2022. Toward assessing absolute environmental sustainability of chemical pollution. *Environ. Sci. Technol.* 56, 4779–4787. <https://doi.org/10.1021/acs.est.1c06098>.
- Krachler, M., Shoty, W., 2009. Trace and ultratrace metals in bottled waters: Survey of sources worldwide and comparison with refillable metal bottles. *Sci. Tot. Environ.* 407, 1089–1096. <https://doi.org/10.1016/j.scitotenv.2008.10.014>.
- Larson, R.A., Brooks, G.R., Devine, B., Schwing, P.T., Holmes, C.W., Jilbert, T., Reichart, G.J., 2015. Elemental signature of terrigenous sediment runoff as recorded in coastal salt ponds: US Virgin Islands. *Appl. Geochem.* 63, 573–585. <https://doi.org/10.1016/j.apgeochem.2015.01.008>.
- Le Bouteiller, A., Blanchot, J., Rodier, M., 1992. Size distribution patterns of phytoplankton in the western Pacific: towards a generalization for the tropical open ocean. *DeepSea Res* 39, 805–823. [https://doi.org/10.1016/0198-0149\(92\)90123-B](https://doi.org/10.1016/0198-0149(92)90123-B).
- Lee, S.Y., Primavera, J.H., Dahdouh-Guebas, F., McKee, K., Bosire, J.O., Cannicci, S., Diele, K., Fromard, F., Koedam, N., Marchand, C., Mendelssohn, I., Mukherjee, N., Record, S., 2014. Ecological role and services of tropical mangrove ecosystems: a reassessment. *J. Glob. Ecol. Biogeogr.* 23, 726–743. <https://doi.org/10.1111/gcb.12155>.
- Lønborg, C., Müller, M., Butler, E.C.V., Jiang, S., Ooi, S.K., Trinh, D.H., Wong, P.Y., Ali, S. M., Cui, C., Siong, W.B., Yando, E.S., Friess, D.A., Rosentretter, J.A., Eyre, B.D., Martin, P., 2021. Nutrient cycling in tropical and temperate coastal waters: Is latitude making a difference? *Est. Coast. Shelf Sci.* 262, 107571. <https://doi.org/10.1016/j.ecss.2021.107571>.
- Long, E.R., MacDonald, D.D., Smith, S.L., Calder, F.D., 1995. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. *Environ. Manag.* 19, 81–97. <https://doi.org/10.1007/BF02472006>.
- Losfeld, G., L'Huillier, L., Fogliani, B., Jaffré, T., Grison, C., 2015. Mining in New Caledonia: environmental stakes and restoration opportunities. *Environ. Sci. Pollut. Res.* 22, 5592–5607. <https://doi.org/10.1007/s11356-014-3358-x>.
- MacDonald, D.D., Ingersoll, C.G., Berger, T.A., 2000. Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. *Arch. Environ. Contam. Toxicol.* 39, 20–31. <https://doi.org/10.1007/s002440010075>.
- Maggioni, F., Pujo-Pay, M., Aucan, J., Cerrano, C., Calcinai, B., Payri, C., Benzoni, F., Letourneur, Y., Rodolfo-Metalpa, R., 2021. The Bouraké semi-enclosed lagoon (New Caledonia) – a natural laboratory to study the lifelong adaptation of a coral reef ecosystem to extreme environmental conditions. *Biogeosciences* 18, 5117–5140. <https://doi.org/10.5194/bg-18-5117-2021>.
- Marchand, C., Allenbach, M., Lallier-Vergès, E., 2011. Relationships between heavy metals distribution and organic matter cycling in mangrove sediments (Conception Bay, New Caledonia). *Geoderma* 160, 444–456. <https://doi.org/10.1016/j.geoderma.2010.10.015>.
- Marchand, C., Fernandez, J.M., Moreton, B., Landi, L., Lallier-Vergès, E., Baltzer, F., 2012. The partitioning of transitional metals (Fe, Mn, Ni, Cr) in mangrove sediments downstream of a ferralitized ultramafic watershed (New Caledonia). *Chem. Geol.* 300–301, 70–80. <https://doi.org/10.1016/j.chemgeo.2012.01.018>.
- Marchand, C., Fernandez, J.M., Moreton, B., 2016. Trace metal geochemistry in mangrove sediments and their transfer to mangrove plants (New Caledonia). *Sci. Tot. Environ.* 562, 216–227. <https://doi.org/10.1016/j.scitotenv.2016.03.206>.
- Matthai, C., Birch, G., 2001. Detection of anthropogenic Cu, Pb, and Zn in continental shelf sediments off Sydney, Australia: A new approach using normalisation with cobalt. *Mar. Pollut. Bull.* 42, 1055–1063. [https://doi.org/10.1016/S0025-326X\(01\)00068-6](https://doi.org/10.1016/S0025-326X(01)00068-6).
- Maurizot, P., Sevin, B., Lesimple, S., Bailly, L., Iseppi, M., Robineau, B., 2020b. Chapter 10: Mineral resources and prospectivity of the ultramafic rocks of New Caledonia. *Geol. Soc. Lond. Mem.* 51, 247–277. <https://doi.org/10.1144/m51-2016-17>.
- Maurizot, P., Sevin, B., Lesimple, S., Collot, J., Jeanpert, J., Bailly, L., Robineau, B., Patriat, M., Etienne, S., Monnin, C., 2020a. Chapter 9: Mineral resources and prospectivity of non-ultramafic rocks of New Caledonia. *Geol. Soc. Lond. Mem.* 51, 215–245. <https://doi.org/10.1144/m51-2016-9>.
- Mc Kergow, L.A., Prosser, I.P., Hughes, A.O., Brodie, J., 2005. Sources of sediment to the Great Barrier Reef world heritage area. *Mar. Pollut. Bull.* 51, 200–211. <https://doi.org/10.1016/j.marpolbul.2004.11.029>.
- McCready, S., Birch, G., Long, E.R., 2006. Metallic and organic contaminants in sediments of Sydney Harbour, Australia and vicinity - a chemical dataset for evaluating sediment quality guidelines. *Environ. Int.* 32, 455–465. <https://doi.org/10.1016/j.envint.2005.10.006>.
- Mentzel, S., Nathan, R., Noyes, P., Brix, K.V., Moe, J., Rohr, J.R., Verheyen, J., den Brink, V., Stauber, J., 2023. Evaluating the effects of climate change and chemical, physical, and biological stressors on nearshore coral reefs: A case study in the Great Barrier Reef, Australia. *Int. Environ. Assess. Manag.* 20, 401–418. <https://doi.org/10.1002/ieam.4871>.
- Merrot, P., Juillot, F., Noël, V., Lefebvre, P., Brest, J., Menguy, N., Guigner, J.M., Blondeau, M., Viollier, E., Fernandez, J.M., Moreton, B., Bargar, J.R., Morin, G., 2019. Nickel and iron partitioning between clay minerals, Fe-oxides and Sulfides in lagoon sediments from New Caledonia. *Sci. Tot. Environ.* 689, 1212–1227. <https://doi.org/10.1016/j.scitotenv.2019.06.274>.
- Merrot, P., Juillot, F., Le Pape, P., Lefebvre, P., Brest, J., Kieffer, I., Menguy, N., Viollier, E., Fernandez, J.M., Moreton, B., Radakovitch, O., Morin, G., 2021. Comparative Cr and Mn speciation across a shore-to-reef gradient in lagoon sediments downstream of Cr-rich Ferralsols upon ultramafic rocks in New Caledonia. *J. Geochem. Explo.* 229, 106845. <https://doi.org/10.1016/j.gexplo.2021.106845>.
- Merrot, P., Juillot, F., Flipo, L., Tharaud, M., Viollier, E., Noël, V., Le Pape, P., Fernandez, J.M., Moreton, B., Morin, G., 2022. Bioavailability of chromium, nickel, iron and manganese in relation to their speciation in coastal sediments downstream of ultramafic catchments: a case study in New Caledonia. *Chemosphere* 302, 134643. <https://doi.org/10.1016/j.chemosphere.2022.134643>.
- Mohammed, E.H., Wang, G.J., 2010. The effects of nickel on the reproductive ability of three different marine copepods. *Ecotoxicol* 19, 911–916. <https://doi.org/10.1007/s10646-010-0471-6>.
- Molnar, N., Welsh, D.T., Marchand, C., Deborde, J., Meziane, T., 2013. Impacts of shrimp farm effluent on water quality, benthic metabolism and N-dynamics in a mangrove forest (New Caledonia). *Est. Coast. Shelf Sci.* 117, 12–21. <https://doi.org/10.1016/j.ecss.2012.07.012>.
- Morel, F.M.M., Milligan, A.J., Saito, M.A., 2003. Marine bioinorganic chemistry: The role of trace metals in the oceanic cycles of major nutrients. *Treatise Geochem.* 6, 113–143. <https://doi.org/10.1016/B0-08-043751-6/06108-9>.
- Neveux, J., de Billy, G., 1986. Spectrofluorometric determination of chlorophylls and pheophytins. Their distribution in the western part of the Indian Ocean (July to August 1979). *DeepSea Res* 33, 1–14. [https://doi.org/10.1016/0198-0149\(86\)90104-4](https://doi.org/10.1016/0198-0149(86)90104-4).
- Ni, X., Wan, L., Liang, P., Zheng, R., Lin, Z., Chen, R., Pei, M., Shen, Y., 2020. The acute toxic effects of hexavalent chromium on the liver of marine medaka (*Oryzias melastigma*). *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* 231, 108734. <https://doi.org/10.1016/j.cbpc.2020.108734>.
- Noël, V., Morin, G., Juillot, F., Marchand, C., Brest, J., Bargar, J., Muñoz, M., Marakovic, G., Ardo, S., Brown, Jr.G.E., 2015. Ni cycling in mangrove sediments from New Caledonia. *Geochim. Cosmochim. Acta* 169, 82–98. <https://doi.org/10.1016/j.gca.2015.07.024>.
- Ogwu, M.C., Izah, S.C., Sawyer, W.E., Amabie, T., 2025. Environmental Risk Assessment of Trace Metal Pollution: A Statistical Perspective. *Environ. Geochem. Health* 47, 94. <https://doi.org/10.1007/s10653-025-02405-z>.
- Pagano, M., Rodier, M., Laval, M., Varillon, D., Guilloux, L., Dupouy, C., Devenon, J.L., Chevalier, C., 2025. Zooplankton in Kone Lagoon (New Caledonia): Natural variability versus mining effects. *Mar. Pollut. Bull.* 210, 117302. <https://doi.org/10.1016/j.marpolbul.2024.117302>.
- Pardo, J.C.F., Poste, A.E., Frigstad, H., Quintana, C.O., Trannum, H.C., 2023. The interplay between terrestrial organic matter and benthic macrofauna: framework, synthesis, and perspectives. *Ecosphere* 14, e4492. <https://doi.org/10.1002/ecsc.2.4492>.
- Pasquet, C., Le Monier, P., Monna, F., Durllet, C., Brigaud, B., Losno, R., Chateau, C., Laporte-Magoni, C., Gunkel-Grillon, P., 2016. Impact of nickel mining in New Caledonia assessed by compositional data analysis of lichens, 1 December 2016, Article number Springer Open Access 5 (1), 2022. <https://doi.org/10.1186/s40064-016-3681-4>.
- Pasquet, C., Monna, F., van Oort, F., Gunkel-Grillon, P., Laporte Magoni, C., Losno, R., Chateau, C., 2018. Mobility of Ni, Co, and Mn in ultramafic mining soils of New Caledonia, assessed by kinetic EDTA extractions. *Environ. Monit. Assess.* 190, 638. <https://doi.org/10.1007/s10661-018-7029-0>.
- Payri, C.E., Allain, V., Aucan, J., David, C., David, V., Dutheil, C., Loubersac, L., Menkes, C., Pelletier, B., Pestana, G., 2019. Chapter 27 – New Caledonia. *World Seas: An Environmental Evaluation*, 2nd edition. Elsevier, pp. 593–618. <https://doi.org/10.1016/B978-0-08-100853-9.00035-X>.
- Pérez-Ruzafa, A., De Pascalis, F., Ghezzi, M., Quisoe-Becerra, J.L., Hernández-García, R., Muñoz, I., Vergara, C., Pérez-Ruzafa, I.M., Umgieser, G., Marcos, C., 2019. Connectivity between coastal lagoons and sea: Asymmetrical effects on assemblages' and populations' structure. *Estuar. Coast. Shelf Sci.* 2016, 171–186. <https://doi.org/10.1016/j.ecss.2018.02.031>.
- Pinazo, C., Bujan, S., Douillet, P., Fichez, R., Grenz, C., Maurin, A., 2004. Impact of wind and freshwater inputs on phytoplankton biomass in the coral reef lagoon of New Caledonia during the summer climatic period: a coupled three-dimensional biogeochemical modelling approach. *Coral Reefs* 23, 281–296. <https://doi.org/10.1007/s00338-004-0378-x>.
- Popoola, S.O., Nubi, A.O., Unyimadu, J.P., Ladigbolu, I.A., Fabunmi, I.A., Udochu, U., Nwamba, E., Oba, I.A., Mordi, S., Adamu, S., 2023. Pollution indices and ecological risk assessment of major elements and trace metals in the marine sediment of the western Nigeria continental shelf, Gulf of Guinea. *Sci. Afr.* 22, e01923. <https://doi.org/10.1016/j.sciaf.2023.e01923>.
- Pujo-Pay, M., Raimbault, P., 1994. Improvement of the wet-oxidation procedure for simultaneous determination of particulate organic nitrogen and phosphorus collected on filters. *Mar. Ecol. Prog. Ser.* 105, 203–207. <https://doi.org/10.3354/meps105203>.
- Quesnel, B., Boulvais, P., Gautier, P., Cathelineau, M., John, C.M., Dierick, M., Agrinier, P., Drouillet, M., 2016. Paired stable isotopes (O, C) and clumped isotope thermometry of magnesite and silica veins in the New Caledonia Peridotite Nappe. *Geochim. Cosmochim. Acta* 183, 234–249. <https://doi.org/10.1016/j.gca.2016.03.021>.

- Ranjbar, J.A., Riyahi, B.A., Shadmehri, T.A., Jadot, C., 2017. Spatial distribution, ecological and health risk assessment of heavy metals in marine surface sediments and coastal seawaters of fringing coral reefs of the Persian Gulf, Iran. *Chemosphere* 185, 1090–1111. <https://doi.org/10.1016/j.chemosphere.2017.07.110>.
- Rodier, M., Pagano, M., Lhomond, L., Péricad, J.P., Guilloux, L., Devenon, J.L., Chevalier, C., 2024. Effects of physical forcing on short-term plankton dynamics in a narrow coral reef lagoon (Ouan, New Caledonia): a two-week high-frequency study. *J. Plankton Res.* 46, 202–218. <https://doi.org/10.1093/plankt/fbae004>.
- Ruan, L., Lin, W., Shi, H., Wang, C., Chen, D., Zou, C., Ren, J., Li, X., 2020. Characterization of a novel extracellular Cu-Zn superoxide dismutase from *Rimicaris exoculata* living around deep-sea hydrothermal vent. *Int. J. Biol. Macromol.* 163, 2346–2356. <https://doi.org/10.1016/j.ijbiomac.2020.09.128>.
- Salmanighabeshi, S., Palomo-Marín, M.R., Bernalte, E., Rueda-Holgado, F., Miró-Rodríguez, C., Fadic-Ruiz, X., Vidal-Cortez, V., Cereceda-Balic, F., Pinilla-Gil, E., 2015. Long-term assessment of ecological risk from deposition of elemental pollutants in the vicinity of the industrial area of Puchuncaví-Ventanas, central Chile, 335–343. *Sci. Tot. Environ.* 527–528. <https://doi.org/10.1016/j.scitotenv.2015.05.010>.
- Salomons, W., Förstner, U., 1984. Sediments and the Transport of Metals. In: *Metals in the Hydrocycle*. Springer, Berlin, Heidelberg. [https://doi.org/10.1007/978-3-642-69325-0\\_3](https://doi.org/10.1007/978-3-642-69325-0_3).
- Sellier, V., Navratil, O., Lacey, J.P., Allenbach, M., Lefèvre, I., Evrard, O., 2021. Reconstructing the impact of nickel mining activities on sediment supply to the rivers and the lagoon of South Pacific Islands: Lessons learnt from the Thio early mining site (New Caledonia). *Geomorphology* 372, 107459. <https://doi.org/10.1016/j.geomorph.2020.107459>.
- Serrano, B., Aubert, A., Stemann, L., Rossi, N., Jamet, J.L., 2016. Proposition of indicators of anthropogenic pressure in the Bay of Toulon (Mediterranean Sea) based on zooplankton time-series. *Cont. Shelf Res.* 121, 3–12. <https://doi.org/10.1016/j.csr.2016.01.016>.
- Silveira, C.B., Cavalcanti, G.S., Walter, J.M., Silva-Lima, A.W., Dinsdale, E.A., Bourne, D. G., Thompson, C.C., Thompson, F.L., 2017. Microbial processes driving coral reef organic carbon flow. *FEMS Microbiol. Rev.* 41, 575–595. <https://doi.org/10.1093/femsre/fux018>.
- Summers, J.K., Wade, T.L., Engle, V.D., 1996. Normalization of metal concentrations in estuarine sediments from the Gulf of Mexico. *Estuaries* 19, 581–594. <https://doi.org/10.2307/1352519>.
- Twining, B.S., Rauschenberg, S., Morton, P.L., Ohnemus, D.C., Lam, P.J., 2015. Comparison of particulate trace element concentrations in the North Atlantic Ocean as determined with discrete bottle sampling and in situ pumping. *Deep Sea Res. Part II* 116, 273–282. <https://doi.org/10.1016/j.dsr2.2014.11.005>.
- USEPA (1996) Method 3050B: Acid Digestion of Sediments, Sludges, and Soils, Revision 2. Washington, DC, 12pp.
- Varrica, D., Lo Medico, F., Zuccolini, M.V., Miola, M., Alaimo, M.G., 2024. Geochemical baseline values determination and spatial distribution of trace elements in topsoils: an application in Sicily region (Italy). *Sci. Tot. Environ.* 955, 176951. <https://doi.org/10.1016/j.scitotenv.2024.176951b>.
- Wang, W.X., 2002. Interactions of trace metals and different marine food chains. *Mar. Ecol. Prog. Ser.* 243, 295–309. <https://doi.org/10.3354/meps243295>.
- Wang, Y., Hu, R., Liu, W., Zhang, X., Lin, J., Zhu, L., Li, J., Xu, Y., 2025. Traceability of heavy metal contamination in surface sediments and source sink patterns in waters of the Miaodao Archipelago: Combined effects of natural factors and human activities. *Reg. Stud. Mar. Sci.* 89, 104280. <https://doi.org/10.1016/j.rsma.2025.104280>.
- Wedepohl, K.H., 1995. The composition of continental crust. *Geochim. Cosmochim. Acta* 59, 1217–1232. [https://doi.org/10.1016/0016-7037\(95\)00038-2](https://doi.org/10.1016/0016-7037(95)00038-2).
- Wilson, G.P., Lloyd, J.M., Khan, N.S., Kemp, A.C., 2024. Stable carbon isotopes and bulk-sediment geochemistry as indicators of relative sea-level change in tidal marshes, mangroves and isolation basins: Application and developments. *Quat. Sci. Rev.* 340, 108855. <https://doi.org/10.1016/j.quascirev.2024.108855>.
- Windom, H.L., Schropp, S.J., Calder, F.D., Ryan, J.D., Smith, R.G., Burney, L.C., Lewis, F. G., Rawlinson, C.H., 1989. Natural trace metal concentrations in estuarine and coastal marine sediments in the southeastern United States. *Environ. Sci. Technol.* 23, 314–320. <https://doi.org/10.1021/es00180a008>.
- Yu, G.B., Liu, Y., Yu, S., Wu, S.C., Leung, A.O., Luo, X.S., Xu, B., Li, H.B., Wong, M.H., 2011. Inconsistency and comprehensiveness of risk assessments for heavy metals in urban surface sediments. *Chemosphere* 85, 1080–1087. <https://doi.org/10.1016/j.chemosphere.2011.07.039>.