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Assessment of spatial distribution of organic contaminants and metallic compounds on a tropical island' coral reef fish communities

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ABSTRACT

The New Caledonian archipelago is an important hotspot of marine biodiversity. Due to mining activities, urbanization, and industrialization, significant amounts of contaminants are discharged into the lagoon. This study analysed the concentrations, spatial distribution, and potential drivers of 14 *metallic compounds and trace elements* (*MTEs*) and 22 persistent organic pollutants (POPs) in ~400 coral reef fish sampled from various sites around New Caledonia, across a gradient from mining centers to remote, uninhabited locations. Boosted regression trees modelling explained between 61 and 86 % of the global variation in MTEs and POPs concentration. Fish body size emerged as the most important correlate of MTEs and POPs concentrations in coral reef fish. Monthly rainfalls were the second most important variable for POPs, whereas the reef area was the second variable explaining MTE concentrations. Our modelling approach allowed us to predict and map the distribution of concentrations at the fish community level for 17 contaminants (9 MTEs and 8 POPs). Predicted concentrations ranged from ~1.5 $ng.g^{-1}$ (β-endosulfan) to ~11.5 $\mu g.g^{-1}$ (Ni), and revealed a widespread contamination throughout the lagoon, from the coast to the barrier reef. Contamination by mining-related elements (Ni, Cr…) were clearly influenced by the surface area of mining registry and to lithology to a lesser extent, whereas Hg contamination strongly depended on biological variables. Our study is the largest of its kind at the archipelago scale, combining data on 36 contaminants in ~400 fish samples with a modelling framework offering insights into underlying processes and spatial data for policy use.

1. Introduction

Coral reef ecosystems worldwide are increasingly threatened by the complex interaction of natural and anthropogenic factors (Graham et al., 2008, 2014; Riegl and Purkis, 2015; Hughes et al., 2018, 2019; Souter et al., 2021). Among the most critical environmental disturbances, pollution driven by human activities—particularly urban and industrial expansion—has led to widespread contamination through runoff (rivers, coastal erosion, waste discharge, etc.), posing a significant risk to both ecosystems and human health. Over the past century, the rapid growth of organic chemical industries has drastically increased the production and release of anthropogenic chemicals, including metallic compounds and trace elements (MTEs) (Phillips, 1995), as well as persistent organic pollutants (POPs). These pollutants, which include polychlorinated biphenyls (PCBs) (Robertson and Hansen, 2001) and pesticides (de Mora et al., 2004), are highly resistant to degradation, allowing them to accumulate in marine food webs and ultimately threaten human health through seafood consumption. Furthermore, the physicochemical properties of these contaminants—such as lipophilicity, resistance to physical, chemical, and biological degradation, as well as semi-volatility—facilitate their long-range transport and accumulation in marine organisms (Phillips, 1995). This persistence can lead to

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biomagnification along trophic webs, posing increasing risks to higher-level consumers (Kelly et al., 2007; Briand et al., 2014; Fey et al., 2019).

The half-life of contaminants in the marine environment is estimated to be at least a decade for the most persistent PCBs (Sinkkonen and Paasivirta, 2000; Robertson and Hansen, 2001), several years to a decade for some MTEs such as mercury (Hg) (Lodenius, 1991), and several months to years for most pesticides (Hellawell, 1988). Following their release into the marine environment, some contaminants can be accumulated by organisms at different trophic positions (Van Ael et al., 2012; Dummee et al., 2012). Carnivorous fish, mainly long-lived species, can bioaccumulate high concentrations of MTEs (e.g., Cd and Hg) or organochlorine pollutants in their tissues (e.g., Adams and McMichael Jr, 1999; Wafo et al., 2012). Fish are particularly informative for assessing the contamination status and distribution of pollutants, especially if they are sedentary or territorial, inhabit benthic habitats, and occupy a high trophic position (carnivores, top predators) (e.g., Kojadinovic et al., 2007; Dierking et al., 2009). At the same time, contamination of fishes raises concerns as they constitute a major pathway for human exposure to various chemical contaminants (Martí-Cid et al., 2007; Storelli, 2008). The numerous health benefits associated with fish consumption, a major source of vitamins, omega-3 fatty acids and high-quality proteins, can thus be compromised by the presence of contaminants, which can have harmful effects on the human body if ingested in toxic quantities (Bosch et al., 2016).

The coral reefs of the New Caledonian archipelago in the Coral Sea (South Pacific) represent a major global biodiversity hotspot (Myers et al., 2000). Listed as a UNESCO World Heritage site since 2008, this designation highlights their global significance, exceptional natural beauty, and rich biodiversity. The archipelago hosts the world's largest lagoon and the second-largest coral barrier reef after Australia's Great Barrier Reef. Moreover, it contains one-third of the world's most remote reefs, largely untouched by human activity or pollution (Januchowski-Hartley et al., 2020). However, despite their importance as a major natural, recreational, and fishery resource, the coral reefs of New Caledonia are under increasing anthropogenic pressure, primarily due to mining activities, agricultural development, industrialization, and a recent and fast urbanization. New Caledonian soils are naturally rich in cobalt (Co), chromium (Cr), iron (Fe), manganese (Mn), and mostly nickel (Ni). New Caledonia holds around 10 % of the world's nickel resources (Grandcolas et al., 2008; Losfeld et al., 2015). Numerous open-pit mines have been in operation since the late 19th century. Intensive mining activities, combined with natural soil erosion caused by tropical rainfalls, result in significant sediment deposition (Ouillon et al., 2010; Garcin et al., 2013) and contamination of coastal waters (Hédouin et al., 2009). In addition, the expansion of industrial infrastructure and urban development, as well as the use of pesticides in agriculture, exacerbate potential contamination of terrestrial as well as coastal marine ecosystems. Thus, New Caledonia represents a critical case for understanding the impact of urban, agricultural, and industrial pollution on coral reef ecosystems. Despite its global ecological importance, the archipelago faces increasing anthropogenic pressures, making the need for large-scale contamination assessments particularly urgent. However, data on contamination in the archipelago exhibit significant gaps. Despite studies conducted on various marine species in New Caledonia, ranging from bivalves to fish (e.g., Bustamante et al., 2000, 2003; Hédouin et al., 2018; Metian et al., 2005, 2008; Bonnet et al., 2014), no study has yet attempted to evaluate the extent of coral reef fish contamination at a community level, thus considering both the effects of variable bioaccumulation of contaminants across fish species and the variable composition and structure of fish assemblages across wide geographic and human impact gradients.

In this study, we assessed the contamination of coral reef fish communities in New Caledonia, spanning from coastal areas to the barrier reef, and across an isolation gradient—from urbanized and industrialized zones to geographically remote locations with minimal to no human influence. To achieve this, our work followed two phases. In the first phase, we modelled coral reef fish contamination using concentration data from 392 individual fish, evaluating the influence of various biological, human-related, biogeographical and environmental variables on contamination concentrations. This first phase allowed us to provide data on 14 metallic trace elements (MTEs) and 22 persistent organic pollutants (POPs). In the second phase, we then integrated these results at a fish community level using a database of 1833 underwater visual surveys on fish abundance and size (D'Agata et al., 2016; Januchowski-Hartley et al., 2020) to predict and map contaminant concentrations per 100 g of fish across the archipelago.

2. Materials and methods

2.1. Sampling sites and sampling population

New Caledonia is an archipelago located in the southwest Pacific Ocean (Fig. 1). The main island, known as "Grande Terre," stretches for about 500 km long and 50 km wide. It is surrounded by the world's second-largest barrier reef, stretching over about 1500 km, which delineate a vast lagoon of approximately 22,000 km^2 (Andréfouët et al., 2009). The major characteristics of this lagoon are its relatively shallow depth, rarely exceeding 50 m, and its oligotrophic to mesotrophic nature (Dupouy et al., 2010; Fichez et al., 2010). The archipelago also includes extensive atoll reefs (Chesterfield-Bellona, Entrecasteaux, Astrolabe), three large high islands (the Loyalty Islands), and several smaller islands. The Chesterfield-Bellona coral reef complex delimits a ~ 13,700 km^2 lagoon is located hundreds of kilometers to the west of the main island (Fig. 1) and its scarce islets are uninhabited. The distribution of human population density follows a clear linear gradient, from the main city (Nouméa, ~98,000 inhabitants) (ISEE, 2019), to the less populated areas (north of the main island and the Loyalty islands), and uninhabited islets in the far north (i.e. Entrecasteaux reefs).

Fish were sampled at 11 sites throughout New Caledonia in 2011 (different sites around Nouméa), 2012 (Moindou), 2017 (Entrecasteaux sites), 2018 (Ouvéa) or 2021 (Walpole) depending on the site (Fig. 1). Some sites close to the Nouméa urban area are potentially exposed to various sources of anthropogenic pollution, such as industrial activities and wastewater discharges. Other sites on the west coast are dedicated to agricultural purposes, while other remote areas are less influenced by anthropogenic influence (e.g., Chesterfield, Entrecasteaux). In total, 392 individuals belonging to 74 species were sampled (Table S1). These species represent a subset of local diversity of coral reef fish (~1400 species, Letourneur et al., 2023). However, the species analysed belong to those that globally make up the largest proportion of total density and biomass, and are among those most consumed by human populations. Furthermore, the sampling aimed to obtain a wide range of fish species with contrasting feeding strategies. Fish species were classified into four major trophic groups: herbivores (mainly consuming macrophytes), omnivores (consuming both animal and plant materials), micro-carnivores (consuming small prey), and macro-carnivores (consuming larger prey), based on known feeding patterns (Parravicini et al., 2020). Fish were either collected directly in the field by angling / spearfishing or using a small amount of non-selective anaesthetic, namely 10 % eugenol diluted in ethanol, or purchased from local fishermen. In all cases, fish were kept in coolers, and each individual was identified and measured (total length, in cm). For each fish, samples of dorsal muscle were taken (~10–20 g wet weight) and frozen at −20 °C until *MTEs* and POPs analysis.

Fish assemblages were studied through 1833 underwater visual transects (UVC), conducted in areas ranging from densely populated to completely isolated and uninhabited, and published elsewhere (D'Agata et al., 2016; Januchowski-Hartley et al., 2020) (Fig. 1).

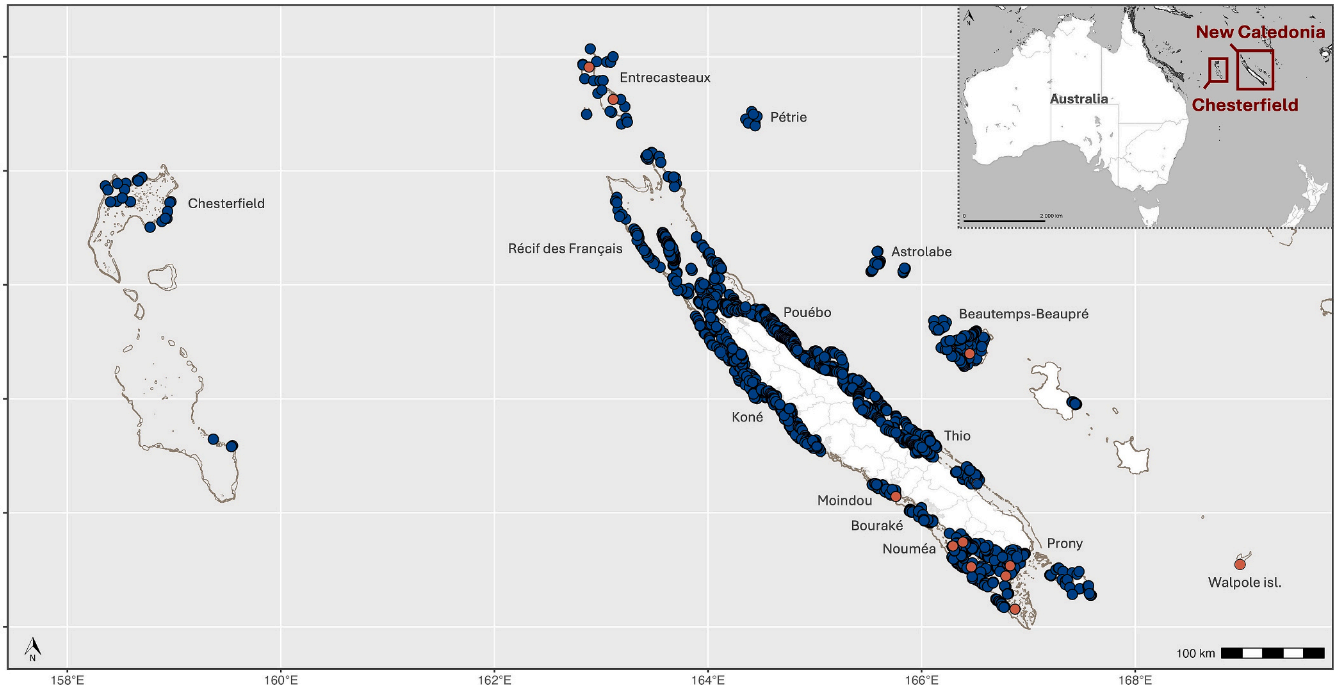

Fig. 1. Locations where coral reef fish assemblages were sampled in 1,833 underwater visual survey (in blue), as well as locations of sites where fish samples were collected for contamination analysis (in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Contaminant analysis

2.2.1. MTEs' analyses

A total of 14 elements were analysed: silver (Ag), arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), mercury (Hg), nickel (Ni), lead (Pb), selenium (Se), vanadium (V), and zinc (Zn). Except for Hg, analyses of these elements were performed following Kojadinovic et al. (2011) method. Around 150–300 mg (dry mass, dm) of lyophilized and powdered samples was analysed using either inductively coupled plasma atomic emission spectroscopy (ICP-AES 5800 VDV, Agilent Technologies ®) or inductively coupled plasma-mass spectrometry (ICP-MS II Series Thermo Fisher Scientific®). Total Hg concentrations were quantified following the procedure described by Bustamante et al. (2006), i.e., in samples ranging from 3 to 10 mg of dry (lyophilized and powdered) samples by atomic absorption spectrometry with an advanced mercury analyzer (AMA 254 ALTEC®). A quality control program was implemented, including the treatment and analysis of certified reference materials (CRMs, which included DOLT-5 dogfish liver and TORT-3 lobster hepatopancreas from the National Research Council, Canada) and blanks alongside the samples. These CRMs were processed and analysed simultaneously with the samples. The recovery rates for the CRMs ranged from 83 % to 115 %. All MTEs concentrations are reported in μg.g^{-1} of fish dry mass (dm), and were conducted on 390 fish samples (Table S1). The detection limits (in μg.g^{-1} dm) were 0.005 μg.g^{-1} (Hg), 0.015 μg.g^{-1} (Ag, Cd), 0.02 μg.g^{-1} (Cr, Co, Pb), 0.03 μg.g^{-1} (Ni), 0.08 μg.g^{-1} (Mn), 0.1 μg.g^{-1} (Cu, Se), 0.2 μg.g^{-1} (As), 0.3 μg.g^{-1} (V), and 3.3 μg.g^{-1} (Fe, Zn). When concentrations were below the detection limit, half of the detection limit was used. Although this approach is common in environmental studies, we are aware that this choice may imply potential biases in the assessment of contaminant concentrations. However, as the detection thresholds are low, the risks of error can reasonably be considered minor and without influence on the overall trends. This was also applied for POPs analyses, below.

2.2.2. POPs' analyses

PCBs comprise a large family of 209 synthetic congeners. A total of 39 congeners were analysed in 237 fish samples (Table S1), and identified by their International Union of Pure and Applied Chemistry (IUPAC) numbers: 17, 18, 20, 28, 31, 44, 49, 52, 60, 70, 74, 82, 87, 92, 95, 99, 101, 105, 110, 118, 128, 136, 138, 141, 149, 151, 153, 156, 170, 174, 177, 180, 183, 187, 191, 194, 195, 196, and 201. The sum of all analysed congeners (ΣPCBs) was calculated, determining the overall PCB load, and is expressed in ng.g^{-1} dm. Quantification was performed using gas chromatography (Agilent Technologies HP6890®) equipped with an electron capture detector at 300 °C and an automatic injector in the column (DB5 J&W column, 60 × 0.32 i.d × 0.25 μm), with helium as the carrier gas. During injection, the temperature is 60 °C, then it increases by 10 °C per minute to 160 °C, and then by 25 °C per minute to 280 °C. The detection limit was 0.01 ng.g^{-1} dm.

Pesticides, a group of chemical compounds widely used to fight against various plant and animal pests (Abhilash and Singh, 2009; Kim et al., 2017), were analysed in this study on 245 fish samples (Table S1), and expressed in ng.g^{-1} dm. Twenty-one pesticides chosen due to their persistence and public health interest were examined, including aldrin, atrazine, α- and cis-chlordane, diazinon, dieldrin, α- and β-endosulfan, endrin, glyphosate, heptachlor, heptachlor epoxide A and B, isodrin, lindane, linuron, malathion, simazine, pp'-DDT, pp'-DDE, and pp'-DDD. Glyphosate was quantified using liquid chromatography, and the other compounds were quantified using gas chromatography–mass spectrometry following the methods fully described in Dierking et al. (2009). The detection limits (DL, in ng.g^{-1} dm) were 0.01 ng.g^{-1} for heptachlor epoxide A and B, 0.02 ng.g^{-1} for linuron and malathion. For aldrin, diazinon, endosulfan II, endrin, heptachlor, lindane, pp'-DDT, pp'-DDE, and pp'-DDD, the DL wass 0.1 ng.g^{-1}, 0.2 ng.g^{-1} for atrazine, dieldrin, and α- and β-endosulfan. Finally, the DL for glyphosate is 1 ng.g^{-1}.

2.3. Potential variables explaining fish contamination

We have considered 18 variables that are known to potentially influence contaminants' concentrations in coral reef fish (Wejieme et al., 2025). These were grouped into four categories encompassing biological characteristics, environment, biogeography, and human-related activities. The first category included six biological variables, i.e., fish body size (TL, in cm), diet, mobility, gregariousness, position in the water column, and the activity period (Parravicini et al., 2021). The second category included three environmental variables, i.e., sea surface temperature (including three “sub-variables”, i.e., min, max and mean SST), monthly rainfalls on a 10-years basis (www.meteo.nc), and lithology data derived from the New Caledonia geological map at a 1/1,000,000 scale (https://georep-dtsi-sgt.opendata.arcgis.com/), which define the characteristics of local soils, such as granulometry, mineralogical composition, etc. The third category included five biogeographical variables: the land areas quantified within buffer zones of 3–30 km using data from 2014’ SPOT-6 images (https://georep.nc), the coral reef areas within 3–30 km radius, and the watershed area within a 30 km buffer zone at a scale of 1/50,000 proposed by the local geological survey (https://georep.nc). Finally, four human-related variables were selected, i.e., the gravity (an indicator of human pressure as a whole; Cinner et al., 2018), the distance between the sampled site and the nearest city, the agricultural land area within a 30 km buffer zone and the mining registry. The latter aggregate data from the active mining registry (concessions, exploration permits, and technical reserves) is compiled from the New Caledonia DIMENC service (https://georep-dtsi-sgt.opendata.arcgis.com/), and provide detailed information on mining titles, owners, concession boundaries, surface and location as well as other aspects related to mining activity. In New Caledonia, where the Ni mining industry predominates, the mining registry is particularly important due to significant open-sky nickel extraction.

2.4. *Modelling individual fish contamination*

We employed boosted regression trees (BRT) to analyze the influence of various variables on contamination concentrations. BRT can handle nonlinear relationships and interactions between variables, generating a series of regression trees, with each new tree explaining the residuals of the previous one (Elith et al., 2008). Four main parameters need to be specified: bag fraction (bf), learning rate (lr), tree complexity (tc), and number of trees (nt). To determine the best model parameters, we tested different combinations of lr and tc to generate multiple BRT models. Consequently, a combination of lr (0.01, 0.005, 0.001) and tc (1 to 5) was used to run the BRT models. The BRT models with the best cross-validated correlation (10-fold) were retained, then refitted by keeping only the variables with importance exceeding 5 % in the model (Elith et al., 2008). BRTs were fitted using the *gbm* package in R (Ridgeway, 2024). This above process constituted the first phase of our analysis.

2.5. *Modelling fish assemblage contamination*

After completing the first phase of our analysis, during which we modelled the contamination of coral reef fish based on the measured concentrations of contaminants while assessing the potential role of various variables, we ran the second phase of our analysis, which consists of two fundamental steps. In the first step, we used an existing dataset on reef fish densities and biomasses in New Caledonia, combined with a stock assessment for the case of Walpole islet (Wantiez et al., 2019). To perform this analysis, we used the *predict.gbm* function from the *gbm* package in R. This function is specifically designed to make predictions based on the regression model established in the first phase (i.e., across 11 sites). This ensure that the same explanatory variables as in the initial model are used. By applying the *predict.gbm* function, we were able to estimate fish contamination concentrations based on density and biomass data. This allowed us to extend the analysis from the first phase to a broader spatial scale. These data were then associated with the contaminant concentrations measured in the first phase; only contaminants with a cross-validation (CV) correlation ≥ 0.6 were retained to ensure the reliability and robustness of our model, leading to the selection of 18 contaminants in total, namely 9 MTEs (Ag, As, Cd, Cr, Cu, Hg, Mn, Ni, and Se) and 8 POPs (atrazine, dieldrin, α- and β-endosulfan, heptachlor epoxide B, pp’-DDDs, pp’-DDTs, and ∑PCBs) (Table S2). It should be noted that the BRT models created in this second phase did not incorporate biological variables, as the collected data were based on fish community censuses. In accordance with the recommendations of Dormann et al. (2013), we removed variables showing collinearity, i.e., a Pearson correlation coefficient > 0.7. Following these tests, six explanatory variables were used in the BRT modelling of MTEs: the distance between the sampling site and the nearest city, reef area within a 30 km buffer zone, watershed area within a 30 km buffer zone, lithology, mining registry within a 30 km buffer zone, and mean SST. For POPs, six variables were used in the BRT models: the distance between the sampling site and the nearest city, reef area within a 30 km buffer zone, gravity, monthly rainfallétu, agricultural land area within a 30 km buffer zone, and mean SST. The second step of our process focused on normalizing contamination for each element, based on a quantity of 100 g of fish per UVC transect. This facilitated mapping at the scale of New Caledonia, providing an overview of predicted contamination concentrations for 9 MTEs and 8 POPs across New Caledonia. Further details on the methodological and modelling framework can be found in Wejieme et al. (2025).

3. Results

3.1. *Concentrations of contaminants in fish*

Overall, the averaged concentrations of MTEs ranged from very low (e.g., Ag, Cd; often below the detection limit, with 58.2 % and 44.9 % of measurements, respectively, falling below this threshold) to high (e.g., As, Fe, and Zn), with other elements at intermediate concentrations (Table S3). Regarding POPs, glyphosate was by far the most abundant pesticide, accounting for ~90.7 % of all detected pesticides, with an average concentration slightly below 139 $ng.g^{-1}$ (Table S3). However, this dominance should be interpreted with caution, as glyphosate was analysed in a smaller subset of fish. Other pesticides showed very low (e.g., pp-DDT, isodrin; often below the detection limit, with 76.8 % and 40.2 % of measurements, respectively, falling below this threshold) to intermediate concentrations (pp’-DDD, β-endosulfan). The sum of PCBs across all samples reached approximately 30 $ng.g^{-1}$ (Table S3).

3.2. *Drivers of fish contamination*

The BRT models explained between 61 % and 86 % of the global variation (i.e., cross-validation, CV) for MTEs and POPs. In fields with high variability, such as ecology or environmental sciences, a 61 %–86 % cross-validation correlation is generally considered good to excellent, with values above 60 % indicating a moderate to strong correlation and values above 80 % reflecting excellent predictive power, capturing most of the underlying patterns. Several recent studies using BRTs in the field of coral reef fish ecology in New Caledonia and the South Pacific display similar figures, with CV correlations ranging from 40 % to 70 % (D'Agata et al., 2016), 42 % to 85 % (Mathon et al., 2024), and 60 % to 87 % (Wejieme et al., 2025). Given the number of variables tested, the number of individuals sampled and the wide range of contaminants measured in our study, the quality of our models is good to excellent, making them amenable to interpretation. Among the explanatory variables, individual size was by far the most influential variable in BRT models for MTEs (27.2 %), PCBs (37.0 %), and pesticides (40.1 %) (Fig. 2). For MTEs, the reef area within a 3 km buffer zone ranked second (15.1 %), followed by soil lithology (11.2 %). Pesticide contamination was influenced by monthly rainfalls as the second key variable (26.0 %), with gregariousness as the third key variable (10.3 %). For PCBs, gregariousness was the second most important variable (21.6 %), followed by maximum SST (20.2 %). Other predictive variables had a lower influence, each contributing <10 % (except land 30 km^2 with

10.1 % for pesticides), depending on the contaminant (Fig. 2, Fig. S1).

While a general pattern emerges—where fish body size is the main driver of contamination—individual compounds (MTEs or POPs) may exhibit deviations from this trend (Table 1). This overarching pattern was observed in several contaminants, but specific elements showed distinct influencing variables. For example, Cu, Fe, Hg, α-chlordane, diazinon and heptachlor, among others, showed high percentages attributed to size as the main variable. However, other contaminants showed different patterns. For example, heptachlor epoxide B strongly depended on monthly rainfalls (66.4 %), As is particularly affected by diet (29.2 %), Co is strongly influenced by lithology (41.6 %), while Cr and Ni showed a strong influence of mining registry, with 34.1 % and 25.4 % attributed to this variable respectively.

For illustrative purposes, we highlighted mining-associated elements (Cr, Mn, and Ni) due to the significance of mining activities in New Caledonia, as well as β-endosulfan as a representative case of POP contamination (the dominant glyphosate was excluded from this analysis due to its low cross-validation coefficient, i.e. <0.6, Table S2).

Ni concentrations in coral reef fish were primarily influenced by the surface area of the mining registry (25.4 %), followed by fish size (23.0 %) and reef area within a 3 km buffer (20.7 %), while gregariousness and lithology played a lesser role (Fig. 3). Cr showed a similar pattern, except for an inversion in the relative importance of gregariousness and lithology. Mn, however, exhibited a distinct trend, where the mining registry was not a significant driver, but lithology and monthly rainfalls were key variables influencing its concentration. β-endosulfan contamination was also influenced by monthly rainfalls (25.4 %) but was primarily driven by fish size (26.4 %) (Fig. 3). Hg represents another noteworthy case due to its well-documented toxicity for public health. Unlike other elements, Hg contamination was predominantly shaped by biological variables—such as fish size, activity period, and diet (Table 1)—without significant associations with biogeographical, human-related, or environmental variables.

3.3. Modelling contamination in coral reef fish communities

The surface area of the watershed within a 30 km buffer emerged as the predominant predictive variable driving the concentrations of MTEs (46.4 %), followed by the distance to the nearest city (30.7 %) and lithology (11.8 %) (Fig. 4). For POPs, the most significant variables stemmed from both human-related and environmental variable categories. PCBs were notably influenced by the distance to the nearest city (62.8 %) and monthly rainfalls (30.5 %), whereas pesticide concentration showed the high significance of agricultural land area within a 30 km radius (51.9 %) followed by the distance to the nearest city (25.8 %) and monthly rainfalls (14.3 %) as drivers of contamination (Fig. 4).

3.4. Mapping contamination distribution on the scale of New Caledonia

Modelled concentrations of contaminants, whether for MTEs or POPs, were generally higher in the southwest lagoon, and lower in the other zones (Fig. 5, Figs. S3 and S4). However, some local exceptions

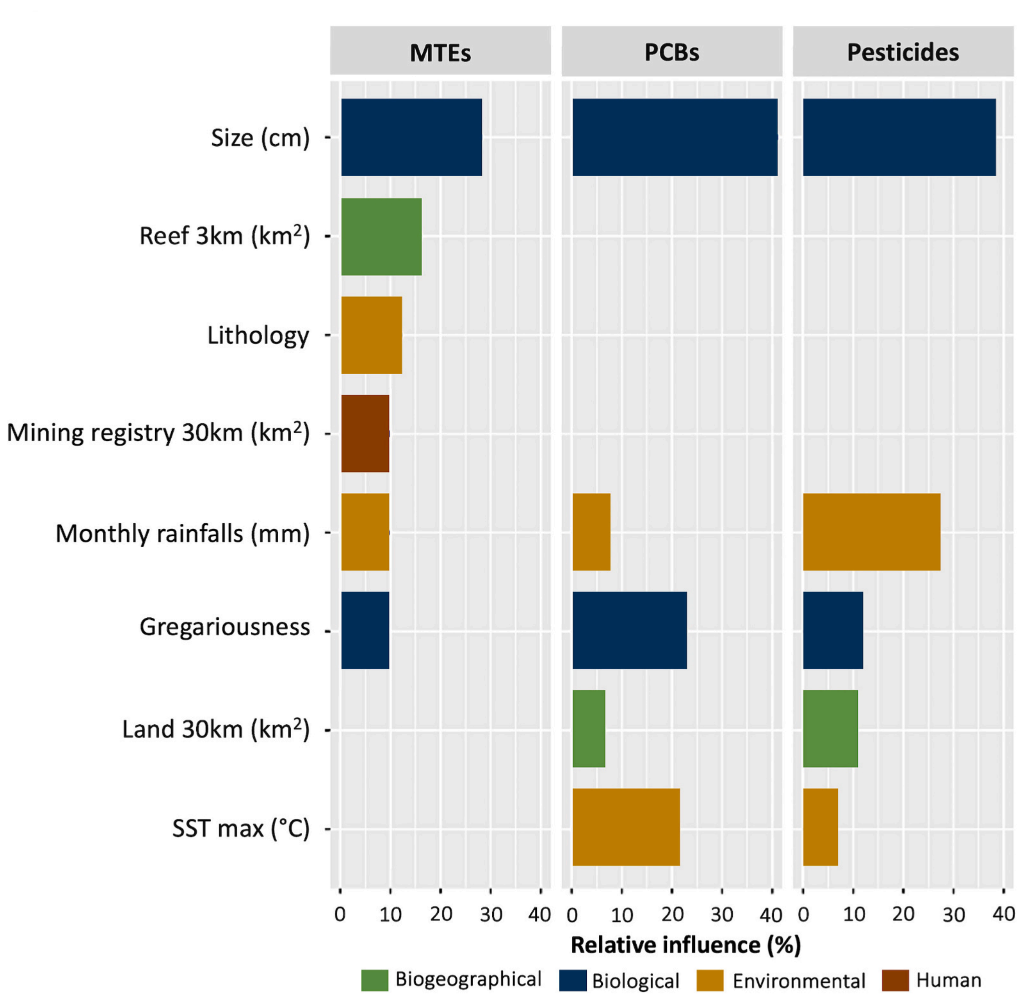

Fig. 2. Summary of the average relative contributions (%) of the height most significant (i.e., > 5%) variables from the four categories of variables (see text) used in BRT modeling explaining their relative influence on coral reef fish contamination. See Suppl Fig. S1 to see the contribution of all variables.

Table 1
Summary of the most important variables driving contaminant concentrations in New Caledonian coral reef fish. Only contribution >10 % were mentioned.

	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
MTEs					
Ag	Monthly rainfalls (51.7 %)	Mining registry (19.7 %)			
As	Diet (29.2 %)	Size (26.7 %)	Activity period (16.5 %)	Reef 3 km (15.2 %)	
Cd	Mobility (25.3 %)	Monthly rainfalls (22.4 %)	Size (16.7 %)	Reef 3 km (13.1 %)	
Co	Lithology (41.6 %)	Size (31.5 %)	Reef 3 km (15 %)	Gregariousness (11.8 %)	
Cr	Mining registry (34.1 %)	Size (26.4 %)	Reef 3 km (16.1 %)	Lithology (11.9 %)	Gregariousness (11.4 %)
Cu	Size (41.1 %)	Reef 3 km (15.5 %)	Gregariousness (10.5 %)		
Fe	Size (27.5 %)	Reef 3 km (21 %)	Lithology (18.4 %)	Gregariousness (12.5 %)	Mining registry (11.1 %)
Hg	Size (36.6 %)	Activity period (29.9 %)	Diet (20.4 %)		
Mn	Size (24.8 %)	Monthly rainfalls (22.3 %)	Reef 3 km (21.6 %)	Lithology (18.9 %)	
Ni	Mining registry (25.4 %)	Size (23 %)	Reef 3 km (20.7 %)	Gregariousness (12.9 %)	Lithology (10.6 %)
Pb	Size (46.9 %)	Diet (20.4 %)			
Se	Size (36.5 %)	Reef 3 km (27.4 %)	Gregariousness (15.5 %)	Mobility (11.4 %)	
POPs					
Aldrin	Size (42.9 %)	Gregariousness (21.6 %)	Land area 30 km (15.5 %)		
Atrazin	Size (17.6 %)	Gravity (16.2 %)	Gregariousness (15.4 %)	SST max (14.1 %)	Land area 30 km (12.6 %)
α-chlordane	Size (58.8 %)	Land area 30 km (21.3 %)			
Diazinon	Size (33.6 %)	Monthly rainfalls (30.4 %)	Activity period (16.7 %)	Land area 30 km (11.2 %)	
Dieldrin	Size (46.4 %)	SST max (23.4 %)	Gregariousness (14.7 %)		
α-endosulfan	Size (45.8 %)	Monthly rainfalls (17.1 %)	Diet (13.9 %)	Gregariousness (11.9 %)	Land area 30 km (11.3 %)
β-endosulfan	Size (26.4 %)	Monthly rainfalls (25.4 %)	Land area 30 km (15.3 %)	Diet (10.5 %)	
Endrin	Size (51.1 %)	Gregariousness (18.1 %)	Monthly rainfalls (16 %)		
Glyphosate	Size (53.8 %)	Gregariousness (21.5 %)	Monthly rainfalls (12.5 %)		
Heptachlor	Size (47.3 %)	Monthly rainfalls (32.8 %)	Diet (19.9 %)		
Heptachlor epoxide A	Size (39.2 %)	Gregariousness (18.4 %)			
Heptachlor epoxide B	Monthly rainfalls (66.4 %)	Size (33.6 %)			
Isodrin	Size (52.2 %)	Gregariousness (26.6 %)	Position water column (11.8 %)		
Lindane	Size (56.2 %)	Monthly rainfalls (18.7 %)	Gregariousness (13.7 %)	Diet (11.4 %)	
Linuron	Land area 30 km (65.3 %)	Size (19.4 %)	Monthly rainfalls (15.4 %)		
Malathion	Monthly rainfalls (57.4 %)	SST max (29.7 %)	Gregariousness (12.9 %)		
pp'-DDD	Size (37.4 %)	Monthly rainfalls (16.5 %)	Gregariousness (13.3 %)	Diet (11.1 %)	Land area 30 km (10.9 %)
pp'-DDE	Size (57.8 %)	Position water column (18.8 %)	Gregariousness (10.3 %)		
pp'-DDT	Monthly rainfalls (89.3 %)	Size (10.7 %)			
Simazine	Monthly rainfalls (79 %)	Diet (12 %)			
∑ PCBs	Size (46.2 %)	Gregariousness (25.8 %)	SST max (19.6 %)		

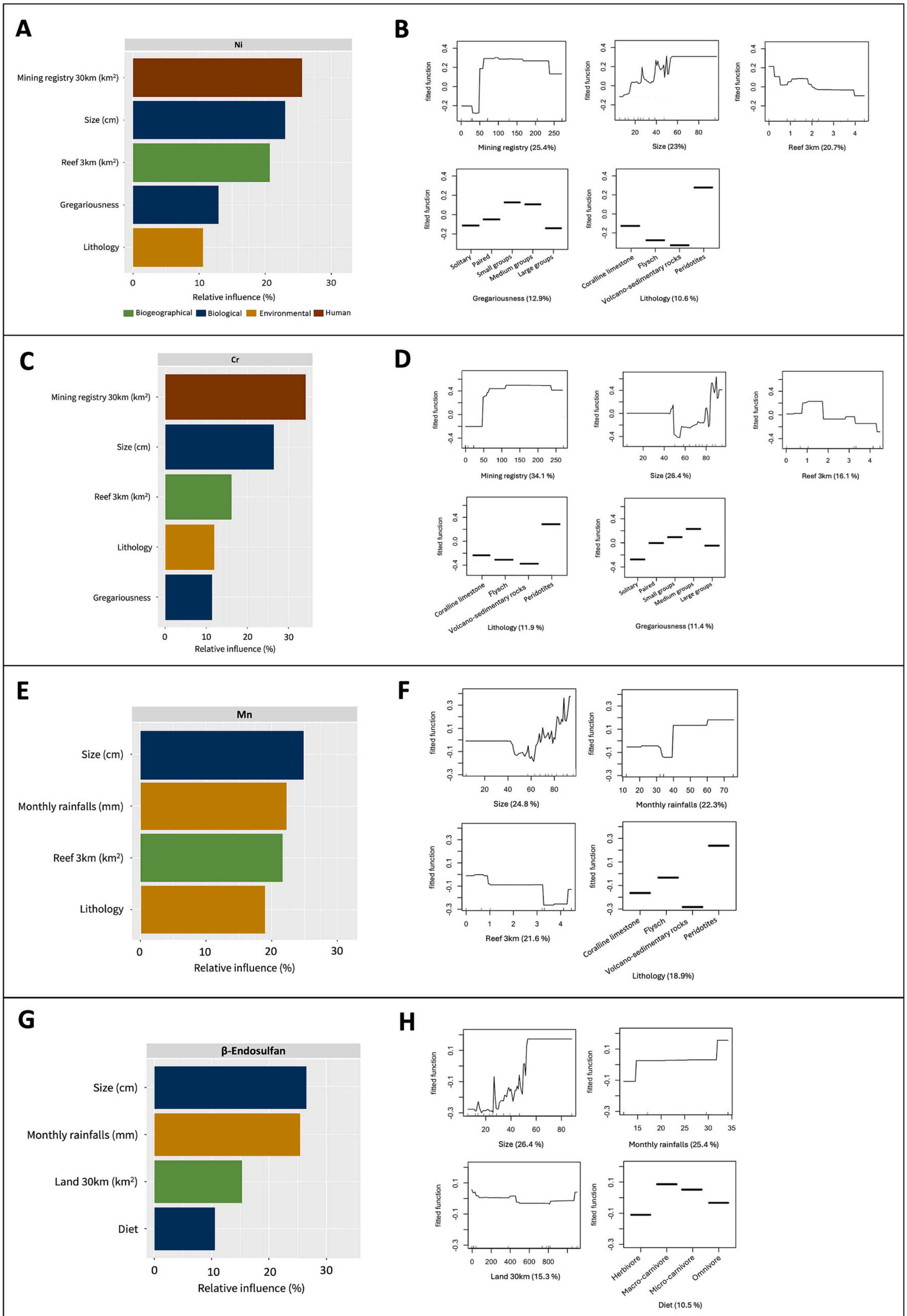

Fig. 3. Summary of relative contributions (%) of the most significant variables (i.e. > 10%) used in BRT explaining contamination in New Caledonian coral reef fish, for Ni (A; CV = 0.61), Cr (C; CV = 0.64), Mn (E; CV = 0.67) and b-endosulfan (G; CV = 0.69) and their fitted functions (ranked by the percentage of relative influence from left to right) (B, D, F and H).

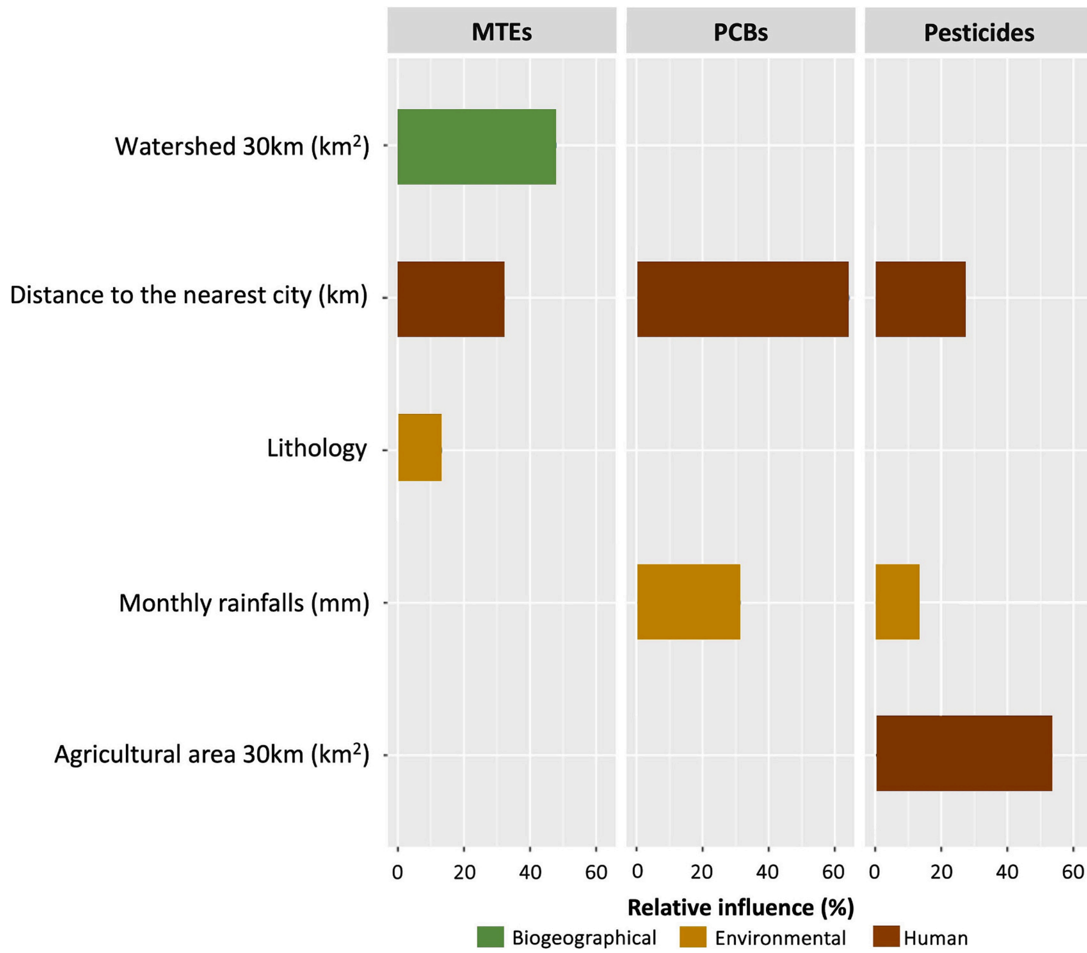

Fig. 4. Summary of the average relative contributions (%) of the most significant variables (i.e., > 10%) used in BRT explaining the relative influence of variables on extrapolated contamination on coral reef fish communities. See Suppl Fig. S2 to see the contribution of all variables.

were found. For instance, the modelled distribution of Ni contamination reveals maximum concentrations at Pouébo (in the northeast coast, see Fig. 1) (11.3 μg.g^{-1}), Nouméa (9.6 μg.g^{-1}), Thio in the east coast (9.4 μg.g^{-1}), Koné (8.9 μg.g^{-1}) and Moindou (7.9 μg.g^{-1}). Lower concentrations were modelled on remote wilderness Astrolabe, Chesterfield, Beautemps-Beaupré and Walpole, ranging from 2.2 μg.g^{-1} to 2.6 μg.g^{-1}. The lowest concentrations were assessed at remote wilderness Petri (1.9 μg-g^{-1}) and "Récif des Français" (0.8 μg.g^{-1}) (Fig. 5A). For most contaminants, a coast to the barrier reef gradient was found, with higher averaged modelled concentration on coastal reefs than on barrier reefs, such as for Ni and β-endosulfan (Fig. 5A, B).

The modelled β-endosulfan contamination revealed maximum concentrations in the west and southwest coasts (see Fig. 1), at Bouraké (14.2 ng.g^{-1}), Prony (13.9 ng.g^{-1}), Moindou (12.3 ng.g^{-1}) and around Nouméa (11.3 ng.g^{-1}). The lowest modelled concentrations were found in remote areas such as at Chesterfield (4.9 ng.g^{-1}), Entrecasteaux (4.2 ng.g^{-1}) and Walpole (1.3 ng.g^{-1}) (Fig. 5B).

4. Discussion

This study is the largest and most comprehensive ever conducted on the New Caledonian archipelago, involving a wide range of sampled species across different sites and analysing numerous potential contaminants. Almost all other studies on coral reef fish are spatially restricted and involve only a few investigated species (e.g. Metian et al., 2013; Bonnet et al., 2014; Briand et al., 2014; Kumar-Roiné et al., 2022). The present study provides a comprehensive assessment of MTE and POP contamination in coral reef fish across New Caledonia, highlighting widespread but spatially variable contamination patterns. While contamination concentrations were generally low, our results reveal consistent anthropogenic influence, particularly for mining-associated elements such as Ni and Cr, and for pesticides like β-endosulfan, with some areas exhibiting higher concentrations linked to local environmental, biogeographical, human-related and biological variables. Modelled concentrations tend to be higher in the southwestern lagoon of New Caledonia, while they are generally lower in areas further away from urbanized zones, including geographically isolated areas without any significant human influence. This finding unsurprisingly underscores and reinforces the impact of human activities on marine ecosystem contamination. Our predictive mapping approach represents an important step towards understanding fish contamination, but it clearly requires validation through additional contaminant analyses, particularly in unsampled areas. As with any modelling process, our approach involves inherent simplifications, approximations, and potential biases related to model parameters and input variables (Wejieme et al., 2025). However, despite these limitations, the model provides valuable insights into large-scale contamination patterns that would be challenging to assess through direct sampling alone.

4.1. Drivers of fish contamination

Individual fish size was the most important variable to explain MTEs and POPs concentrations. MTE concentration in fish is also known to depend on other multiple biological variables, size often being key (Ge et al., 2020; Tanır, 2021; Vetsis et al., 2021; Younis et al., 2021). A similar dependency has been observed for POPs, whose concentration

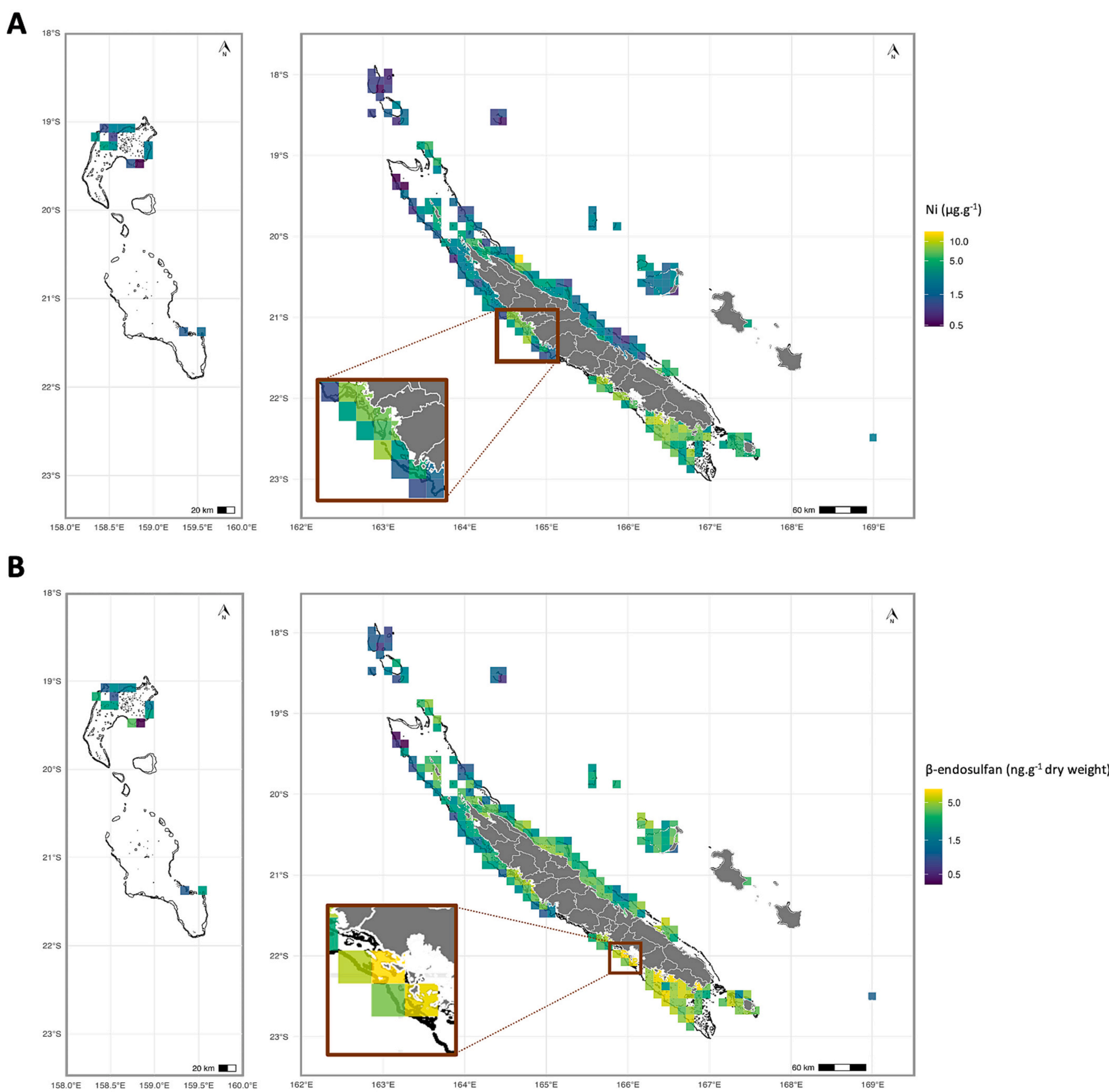

Fig. 5. Maps of modelled Ni (A) and b-endosulfan (B) concentrations in New Caledonian coral reefs fish using BRT with environmental, biogeographic, and human-related variables. The inserts showed examples of coast to barrier reef differences. See Suppl Figs. S3 and S4 for other contaminants.

concentrations in fish and other aquatic organisms are influenced by several variables, including size (Banaee, 2013; Ullah and Zorriehzahra, 2015). Analysis of MTEs revealed that reef size in a 3 km buffer zone and lithology were identified as significant drivers of fish contamination. The importance of reef size lies in its role in providing diverse habitats that support a wide range of fish species, emphasizing the significance of local-scale habitat availability. In contrast, Wejieme et al. (2025) demonstrated that larger reef areas (30 km radius) play a crucial role in assessing contamination at a regional scale. Moreover, Hg contamination exemplifies this multiscale variability, as it is strongly influenced by fish size and dietary habits, regardless of whether it is considered at a local or regional scale. The lithology also plays a significant role in contamination by influencing the content and mobilization of MTEs in the watershed. The nature of the soil, derived from rock weathering, influences the initial content but also the retention of these chemical elements (i.e. adsorbed or trapped within bearing minerals). However, their erosion and the transport of the resulting eroded particles through runoff and rivers to the sea will alter their availability to marine organisms (David et al., 2010) as a result of the input of MTEs in the water system. The results regarding POPs revealed that monthly rainfalls were the most important driver of fish contamination. The introduction of pesticides into aquatic ecosystems is influenced by a multitude of geological and climatic variables, including land slope, hydrography, rainfall intensities, and soil moisture (Schulz, 2004). In addition, landscape changes, mainly due to agricultural practices (deforestation, land cultivation, overgrazing, etc.) (Restrepo et al., 2015; Schmidt et al.,

2018) leads to significant soil erosion. This erosion, in turn, accelerates the degradation of riverine, watershed, and coastal systems, primarily due to the accumulation of fine sediments (Terry et al., 2008; Sellier et al., 2021). These effects are particularly severe in tropical regions, where intense rainfalls—often triggered by tropical depressions and cyclones during the wet season—further exacerbates the issue (Restrepo and Syvitski, 2006; Zhu et al., 2008; Sellier et al., 2021). In the case of PCBs, other key influencing variables include sea surface temperature (SST), proximity to urban areas, and monthly rainfalls. These results are consistent with studies showing that PCB contamination varies depending on many variables such as species, fish size, locations, and environmental conditions (Bayarri et al., 2001; Storelli, 2008; Fey et al., 2019). These various variables influencing PCB fish contamination can be explained by the bioaccumulative behaviour of these chemicals in marine ecosystems. Human activities in urban or industrialized zones can remobilise PCBs present to coastal environments, while SST can influence the bioavailability and spatial distribution of PCBs in aquatic habitats.

The case of Ni needs a particular attention due to its crucial importance for the New Caledonian economy. The ultramafics soils of New Caledonia are naturally rich in Ni but mining exploitation of this element is known for decades without a doubt as a major cause of environmental degradations in the island (Bird et al., 1984). Mining activities, initiated in 1880 and intensified with the mechanization of extractive industries since the 1950s, have led to significant expansion of denuded areas, including mining sites, exploration zones, and mining roads, as well as an increase in mining wastes (Iltis, 1992). Our results revealed that the concentration of Ni in reef fish is mostly influenced by the surface area of the mining registry in a 30 km radius around the sampling area, fish size and reef area in a 3 km buffer zone. Mining activities currently represent the second-largest source of soil contamination by MTEs worldwide (Younger, 2001). Indeed, soils undergo significant leaching of MTEs due to their high concentration, erosion sensitivity and low water retention capacity, leading to prolonged persistence of these elements in the aquatic environment (Singh et al., 2005; Ashraf et al., 2011a, 2011b; Nouri et al., 2008a, 2008b). This contamination is particularly significant in New Caledonia with Ni resources concentrated in ultramafic formations covering ~30 % of the subsoil (Isnard et al., 2016). Mining activities, combined with natural soil erosion due to rainfalls, contribute to high concentrations of Ni, but also Co, Cr, and Mn in New Caledonian coastal waters and are found in high concentrations in fish and benthic meiofauna in the vicinity of metallurgical plants. Their concentrations decreased as one moves further offshore (Dalto et al., 2006; Metian et al., 2013; Bonnet et al., 2014; Briand et al., 2014), thereby threatening local coastal ecosystems and marine organisms (Noel et al., 2014; Noël et al., 2015; Letourneur et al., 2017; Merrot et al., 2019, 2021; Kumar-Roiné et al., 2022). Deforestation and soil stripping leave significant scars on mountain slopes, increasing their landslide sensitivity leading to numerous deposits of terrigenous materials carried by runoff to the hydrographic network, then to the coral reef lagoon. Additionally, the accumulation of excavated waste produced by mining, often deposited directly on steep slopes, undergoes severe erosive processes during rainfalls. The main sources of these deposits include rivers, which drain elements from their watersheds following the alteration of underlying rocks (He et al., 2005; Mohammed et al., 2011).

4.2. *Modelling fish contamination in new Caledonian coral reefs*

Our study highlighted the significant influence of multiple variables on MTE and POP concentrations in coral reef fish communities. Among these, watershed area within a 30 km buffer zone, proximity to the nearest city, and lithology emerged as key drivers of MTE concentrations. In New Caledonia, watersheds exert strong downstream pressure, primarily due to mining activities, significantly impacting both freshwater and marine ecosystems (Richer de Forges and Pascal, 2008). Additionally, river and coastal systems suffer from degradation caused by the excessive influx of fine sediments (Syvitski et al., 2005), consistent with studies reporting high MTE concentrations near metallurgical plants (Dalto et al., 2006; Hédouin et al., 2009, 2011; Bonnet et al., 2014). Significant contamination in mining-related elements (Co, Cr, Mn, Ni) was also observed in non-urban areas, far away from metallurgic plants' sites such as in Thio (the oldest mine of New Caledonia) on the east, lowly inhabited coast. Such cases illustrate the role of past or current mining exploitation (mining registry), and lithologic characteristics already discussed above.

Regarding PCBs, the results emphasize the importance of both human-related and environmental sources with distance to the nearest city and monthly rainfalls representing the predominant variables. Although the production and use of PCBs are now banned, they continue to contaminate the marine environment by leaching from landfill sites (electrical and furniture wastes), industrial wastewaters, and waste incineration by-products, through mechanisms such as spills or direct releases, atmospheric transport (wet and dry deposition), and resuspension of sediments during storm events (Ma et al., 2018; Chakraborty et al., 2022; Luarte et al., 2022). PCBs are present in all compartments of the biosphere, atmospheric and oceanic transport play a crucial role in the dispersion of these contaminants, thus exposing a large portion of living organisms to these substances (Van den Berg et al., 2006). Agricultural land area within a 30 km buffer zone is the most significant driver of pesticides concentration in fish, evidencing that agricultural practices represent a significant link between terrestrial and marine ecosystems. Additionally, distance to the nearest city and monthly rainfalls are also important drivers in pesticide concentrations, underlining significant interactions between anthropogenic and environmental influences in the dispersion of these contaminants. Soil erosion, one of the world's major environmental threats, has particularly accelerated in recent decades due to landscape changes induced by human activities, including land clearing, deforestation (Restrepo et al., 2015), land cultivation (Schmidt et al., 2018) and overgrazing (Stinchcomb et al., 2013). This erosion phenomenon is exacerbated by the rapid development of agricultural production systems to meet growing population demand, which has led to considerable use of numerous pesticides (Hakeem, 2015; Pierart et al., 2015; Rohani, 2023).

However, we can expect for an improvement in New Caledonia, because while used phytosanitary products and pesticide tonnages rose from 2250 to 4380 t between 1983 and 2002 mostly for agriculture (David et al., 2010), their use has fallen sharply, reaching only 50 t of products imported in 2017 (Davar, 2018). These chemicals not only affect targeted pests but also impact the entire environment, including the atmosphere, soil, groundwater, and surface waters (Nsibande and Forbes, 2016), resulting in contamination of aquatic ecosystems (Taha et al., 2014). This pesticide use has led to deterioration of aquatic ecosystems in multiple forms, such as leaching, drift, drainage, and runoff (Cerejeira et al., 2003). In New Caledonia, the combination of erosion linked to mining activities and those associated with agricultural practices, overgrazing by animals (mainly cattle, invasive, non-native deer and feral pigs) and frequent brush fires have significant impacts. In addition, heavy rainfalls during the wet season and the steep slopes of many watersheds greatly facilitate this erosion phenomenon (Danloux and Laganier, 1991; David et al., 2010).

5. Conclusion

This study thus represents a major step forward by providing an unprecedented assessment of coral reef fish community contamination at the scale of the entire archipelago, allowing us to identify the most exposed areas and the key factors influencing contaminant distribution. Our study reveals a widespread presence of MTEs and POPs in coral reef fish across New Caledonia, with concentrations generally ranging from low to moderate. However, even if contaminants were at relatively low concentrations in fish, thereby limiting the current health risk for humans, their interaction can potentially increase their hazardous effects ('cocktail effect') (Fey et al., 2019). This aspect should be further explored in the future. Notably, even remote and uninhabited areas showed contamination, highlighting the potential role of atmospheric and oceanic transport. For example, lindane concentrations in the spotted grouper (*Epinephelus maculatus*) were 1.6 ± 0.1 ng.g^{-1} dw, significantly lower than the 73.3 ± 34.5 ng.g^{-1} dw reported for the star-spotted grouper (*E. hexagonatus*) in French Polynesia (Salvat et al., 2012). Similarly, PCB concentrations in *E. maculatus* (13.4 ± 69.9 ng.g^{-1} dw) were considerably lower than those found in the Mediterranean for the common sole (*Solea solea*; 361.9 ± 190.7 ng.g^{-1} dw; Dierking et al., 2009). These findings provide a crucial foundation for understanding fish contamination patterns in New Caledonian coral reefs. The hypotheses formulated in this study offer key directions for future research to better elucidate the mechanisms driving contamination. Moreover, our results underscore the need for targeted management strategies to mitigate pollution impacts and safeguard marine ecosystems. Integrating these insights into conservation efforts presents a promising pathway for more effective environmental management of New Caledonia's coral reefs in the face of increasing anthropogenic pressures.

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CRediT authorship contribution statement

Noreen Wejieme: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Laurent Vigliola:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Valeriano Parravicini:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Alain Nicolay:** Writing – review & editing. **Emmanuel Wafo:** Writing – review & editing, Formal analysis. **Paco Bustamante:** Writing – review & editing, Methodology, Formal analysis. **Yves Letourneur:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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