



Evidence on the impacts of chemicals arising from human activity on tropical reef-building corals; a systematic map

Dakis-Yaoba Ouédraogo, Mathilde Delaunay, Romain Sordello, Laetitia Hédouin, Magalie Castelin, Olivier Perceval, Isabelle Domart-Coulon, Karen Burga, Christine Ferrier-Pagès, Romane Multon, et al.

► To cite this version:

Dakis-Yaoba Ouédraogo, Mathilde Delaunay, Romain Sordello, Laetitia Hédouin, Magalie Castelin, et al.. Evidence on the impacts of chemicals arising from human activity on tropical reef-building corals; a systematic map. *Environmental Evidence*, 2021, 10 (22), 10.1186/s13750-021-00237-9 . hal-03353843

HAL Id: hal-03353843

<https://hal.science/hal-03353843>

Submitted on 24 Sep 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

SYSTEMATIC MAP

Open Access



Evidence on the impacts of chemicals arising from human activity on tropical reef-building corals; a systematic map

Dakis-Yaoba Ouédraogo^{1*} , Mathilde Delaunay², Romain Sordello², Laetitia Hédouin^{3,4}, Magalie Castelin⁵, Olivier Perceval⁶, Isabelle Domart-Coulon⁷, Karen Burga⁸, Christine Ferrier-Pagès⁹, Romane Multon⁸, Mireille M. M. Guillaume^{3,10}, Clément Léger¹¹, Christophe Calvayrac^{12,13}, Pascale Joannot¹⁴ and Yorick Reyjol²

Abstract

Background: Tropical coral reefs cover ca. 0.1% of the Earth's surface but host an outstanding biodiversity and provide important ecosystem services to millions of people living nearby. They are currently threatened by local stressors (e.g. nutrient enrichment and chemical pollution arising from poor land management, sewage effluents, agriculture, industry) and global stressors (mainly seawater warming and acidification, i.e. climate change). Global and local stressors interact in different ways, but the presence of one stressor often reduces the tolerance to additional stress. While global stressors cannot be mitigated solely by local actions, local stressors can be reduced through ecosystem management, therefore minimizing the impact of climate change on coral reefs. We systematically mapped the evidence of impacts of chemicals arising from anthropogenic activities on tropical reef-building corals, which are the main engineer species of reef ecosystems, to inform decision-makers on the available evidence on this topic.

Methods: We searched the relevant literature using English terms combined in a tested search string in two publication databases (Scopus and Web Of Science Core Collection). The search string combined terms describing the population (tropical reef-building corals) and the exposure (chemicals). We searched for additional literature through three search engines, three dissertations repositories, 11 specialist websites, and through a call to local stakeholders. Titles, abstracts, and full-texts were successively screened using pre-defined eligibility criteria. A database of all studies included in the map with coded metadata was produced. The evidence was described and knowledge clusters and gaps were identified through the distribution and frequency of studies into types of exposure and/or types of outcomes and/or types of study.

Review findings: The initial searches identified 23,403 articles which resulted in 15,177 articles after duplicate removal. Among them, 908 articles were retained after screening process, corresponding to 7937 studies (a study being the combination of a taxon, an exposure, and an outcome). Among these studies, 30.5% dealt with the impact of nutrient enrichment on corals while 25% concerned the impact of human activities without reference to a chemical. The most measured outcomes were those related to the chemical concentration in corals (bioaccumulation, 25.8%), to coral physiology (16.9%), cover (14%), and mortality (9%). Half of the studies (48.4%) were

*Correspondence: dakis.ouedraogo@gmail.com; akis-yaoba.ouedraogo@mnhn.fr

¹ Direction de L'Expertise, Muséum National d'Histoire Naturelle (MNHN), 75005 Paris, France

Full list of author information is available at the end of the article



© The Author(s) 2021. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>. The Creative Commons Public Domain Dedication waiver (<http://creativecommons.org/publicdomain/zero/1.0/>) applies to the data made available in this article, unless otherwise stated in a credit line to the data.

experimental—the exposure was controlled by the researchers—and were conducted in laboratory conditions (39.4%) and in situ (9%). The most studied taxa, exposure, and outcomes were different between experimental and observational studies.

Conclusions: We identified four well-represented subtopics that may be amenable to relevant full syntheses via systematic reviews: (1) evidence on bioaccumulation of chemicals by corals; (2) evidence on the effects of nutrient enrichment on corals; (3) evidence on the effects of human activities on corals; and (4) evidence on the ecotoxicological effects of chemicals on corals (except nutrient enrichment). The systematic map shows that corals in their natural environment can be exposed to many categories of chemicals, and that there is a complete gap in experimental research on the combined effects of more than two categories of chemicals. We therefore encourage research on this topic.

Keywords: Contamination, Hermatypic, Nutrients, Pollution, Scleractinian

Background

Tropical coral reefs cover ca. 0.1% of the Earth's surface but they host an outstanding biodiversity [1] and provide important ecosystem services to millions of people living nearby [2, 3]. Despite their biological and economic importance, 75% of the world's tropical coral reefs are currently threatened by both global and local stressors [2, 4, 5]. While the most prominent global threats are represented by seawater warming and acidification [6], local threats are mainly unsustainable and destructive development of coastal areas, excess sedimentation, overfishing, as well as nutrient and chemical pollution arising from poor land management, agriculture and industry [7, 8]. Global and local stressors interact in different ways, but the presence of one stressor often reduces the physiological tolerance of individuals to additional stress. For example, corals are more sensitive to seawater warming if they are already physiologically stressed by poor water quality [9]. While global stressors cannot be mitigated solely by local actions, local stressors can be reduced through ecosystem management, therefore avoiding the exacerbation of climate change effects by the interaction of multiple stressors [10].

The health of reef ecosystems is largely based on the health of their main engineer species, the reef building corals, which are key organisms responsible for reef accretion, but also form the three-dimensional structures serving as habitat, food and nursery for thousands of other reef organisms. The vast majority of such corals (Hermatypic corals, *sensu* [11]) are colonial scleractinian corals (Cnidaria Hexacorallia) living in association with endosymbiotic dinoflagellate algae belonging to the Symbiodiniaceae family [12]. Symbionts are key to the success of corals in oligotrophic reef waters as they transfer most of the photosynthetically-acquired nutrients to the coral host for its own use [13, 14]. This association is however fragile. Many reviews have now made clear that elevation in seawater temperature above a certain threshold is the main factor responsible for the breakdown of

the coral-algal symbiosis also called coral bleaching (see for example [15]). As symbionts are the main nutritional source for corals, prolonged bleaching condition may ultimately lead to coral death, and affect the overall functioning of coral reef ecosystems. Coral symbiosis is also largely impacted in coastal reefs by water pollution, which is a major threat *per se* [16], but also reduces coral resistance to thermal stress and acidification [17, 18]. According to the type of pollution, the host, the symbionts, or both partners can be impacted through reduced calcification or photosynthesis, enhanced bleaching or cellular damage, and reduced fecundity among other damages [19–21]. The effect of water pollution on corals is a complex subject, due to the vast array of pollutants present in the surrounding environment, and interactions among pollutants, or with other environmental stressors. While several reviews have focused on the subject (e.g. [22, 23]), they often addressed only one source of pollution or class of chemicals such as nutrients [24], herbicides [25], oil [26], or sunscreen ingredients [27]. Furthermore, none of these reviews mention the method used to collect the studies, so they are not reproducible and the risk of bias due to the selection of particular studies cannot be assessed.

In this paper, we thus systematically map the evidence related to the impacts of chemicals arising from human activities on tropical reef-building corals. Such knowledge is vital for an effective ecosystem management and coral reef protection.

Topic identification and stakeholder input

In the French Overseas Territories, coral reefs cover 14,280 km² corresponding to 5% of the world's total coral reef area [28, 29]. France is hence the country with the 4th largest coral reef area in the world, after Indonesia (18% of world total area), Australia (17%) and the Philippines (9%) [29], and therefore has substantial responsibility towards coral reef protection. The French Ministry of Ecology has launched an assignment for a project aiming

to assess the impacts of chemicals and nutrients on coral reefs and to find ways to improve coral reef protection and management at the national scale. The project includes a systematic review in order to gather and analyse the existing knowledge on the impacts of chemicals and nutrients on coral reefs. Because the topic is very broad (all chemicals and all types of coral response should be considered) the first step was to produce a systematic map of evidence, in order to identify relevant knowledge clusters for which evidence can be further analysed in systematic reviews. The review team formulated the primary question of the map and its components, focusing on reef-building corals that are the main engineer species of reef ecosystems, and this was then approved by the French Ministry of Ecology. The French Ministry of Ecology, as well as the French Ministry for Overseas are part of the steering committee of the overall project, and therefore regularly followed the progress of the map.

Objective of the review

Primary question

The primary question of this systematic map is: What evidence exists on the impacts of chemicals on tropical reef-building corals?

Components of the primary question

The above primary question has the following key elements:

Population: All tropical reef-building coral species (hermatypic scleractinian species, *Millepora* species, *Heliopora* species and *Tubipora* species).

Exposure: All natural (e.g. nitrate), geogenic (e.g. nickel) and synthetic chemicals (e.g. diuron) coming from human activities.

Comparator: Population not exposed to chemicals; Population prior to chemical exposure; Population exposed to a different concentration of chemicals.

Outcome: All outcomes related to tropical reef-building corals, from the molecular (e.g. gene expression, enzyme activities) to the community level (e.g. coral cover, species richness).

Methods

The systematic map followed the Collaboration for Environmental Evidence Guidelines and Standards for Evidence Synthesis in Environmental Management [30] and the protocol has been published in Environmental Evidence [31]. A small deviation to the protocol occurred during the review process: because the searches for dissertations gave relatively few records we extracted all search records instead of the first 100 hits. The systematic

map conforms to ROSES reporting standards [32] (see Additional file 1).

Search for articles

Search terms and languages

Searches were performed using search terms exclusively in English language. This search however retrieved articles written in languages other than English, and articles written in English and French were included (see section “Eligibility criteria”). The list of search terms is presented in the next section (see section “Search string”).

Search string

The best combination of search terms obtained after a scoping exercise (i.e. that gave the highest comprehensiveness and specificity, see Additional file 2 in [31]) was (Web Of Science format):

TS=(coral\$ AND (contamin* OR pollut* OR toxicant\$ OR chemical\$ OR "industrial discharge\$" OR runoff OR run-off OR sewage OR eutrophication OR effluent\$ OR waste\$water OR waste-water OR "shipping" OR biocide\$ OR "industrial product\$" OR "consumer product\$" OR "household product\$" OR "biocidal product\$" OR disinfect* OR nutrient\$ OR oil OR metal\$ OR pesticide\$ OR herbicide\$ OR insecticide\$ OR fungicide\$ OR antifoul* OR anti-foul* OR organochlorine\$ OR "flame retardant\$" OR detergent\$ OR "perfluorinated compound\$" OR pharmaceutical\$ OR "personal care product\$" OR cosmetic\$ OR PAH\$ OR petroleum OR hydrocarbon\$ OR microplastic\$ OR nanoparticle\$ OR nano-particle\$ OR "endocrine disrupt*" OR "organic compound\$" OR dispersant\$ OR metalloid\$ OR solvent\$ OR petrochemical\$ OR additive\$ OR preservative\$ OR plasticizer\$ OR hormone\$ OR "transformation product\$" OR "degradation product\$" OR byproduct\$ OR by-product\$ OR sunscreen\$ OR "UV filter\$" OR "ultraviolet filter\$" OR antibiotic\$ OR phthalate\$ OR PCB\$ OR cyanide\$ OR chlordecone OR nickel OR copper OR zinc OR cadmium OR mercury OR iron)).

Estimating the comprehensiveness of the search

To assess the comprehensiveness of the search string, we used a test list of 58 articles considered by the review team as relevant to answer our question and spanning a wide range of chemicals (see Additional file 3 in [31]). The search string retrieved 56 of the 57 articles of the test list indexed in the WOS CC and/or Scopus databases. The article of the test list that was not retrieved on either WOS CC or Scopus was a review about the impact of UV filters on aquatic biota that does not contain the term “coral” in its title, abstract, or keywords. This review reviewed only one article about corals that was

nevertheless retrieved by the search string (Additional file 2 in [31]).

Bibliographic databases

We performed searches on two online multidisciplinary publication databases: Scopus (Elsevier) and WOS CC (Clarivate Analytics) that we can access through a CNRS (the French National Centre for Scientific Research) subscription. Searches were performed on March 19th 2020. The abovementioned search string was adapted to fit the search facilities of the Scopus database (Additional file 2). All search strings used for the different sources are provided in Additional file 2.

We had access to the following WOS CC Citation Indexes:

- Science Citation Index Expanded (SCI-EXPANDED, 1900-present);
- Social Sciences Citation Index (SSCI, 1956-present);
- Arts & Humanities Citation Index (A&HCI, 1975-present);
- Conference Proceedings Citation Index- Science (CPCI-S, 1998-present);
- Conference Proceedings Citation Index- Social Science & Humanities (CPCI-SSH, 1998-present);
- Emerging Sources Citation Index (ESCI, 2015-present);
- Current Chemical Reactions (CCR-EXPANDED, 1985-present, includes Institut National de la Propriété Industrielle structure data back to 1840);
- Index Chemicus (IC, 1993-present).

We had access to all Scopus database (1788-present). No time restriction was applied during searches.

Internet searches

Additional searches of literature were performed using three search engines:

- CORE (<https://core.ac.uk/>);
- Google Scholar (<https://scholar.google.fr/>);
- GreenFILE (www.greeninfoonline.com).

Searches were performed on July 7th 2020 for CORE, and July 8th 2020 for Google Scholar and GreenFile, and the search string developed during the scoping exercise on WOS CC database was adapted to fit the search facilities of these search engines (Additional file 2). In particular, the search string had to be split into six search strings for Google Scholar. Searches were performed on titles, then the results were sorted by relevance and the first 400 hits were extracted. Extraction of results from CORE was done one by one into Zotero using the Zotero

connector for web browser. Results from Google Scholar were extracted using the software Publish or Perish (version 7.15.2643.7260, <https://harzing.com/resources/publish-or-perish>, version accessed 16 March 2020). Results from GreenFile were extracted using the offered export facilities (results can be sent by email in various bibliographic formats e.g. RIS format).

Additionally, we also searched on September 15th 2020 for dissertations in ProQuest Dissertations and Theses (<https://search.proquest.com/>, Publicly Available Content Database), Open Access Theses and Dissertations (<https://oatd.org/>) and the French thesis repository (<https://www.theses.fr/>). The search string was adapted to fit the specificities of each repository (Additional file 2). Searches were performed on titles and all hits were extracted.

Specialist searches

We searched for links or references to relevant articles on the following eleven specialist websites (English- or French-written websites):

- Australian Institute of Marine Science (<https://www.aims.gov.au/>);
- Coral Health and Monitoring Program (NOAA, <https://www.coral.noaa.gov/>);
- Coral traits database (<https://coraltraits.org/>);
- Ecotox knowledge base of the United States Environmental Protection Agency (EPA, <https://cfpub.epa.gov/ecotox/>);
- French Coral Reef Initiative (IFRECOR, <https://ifrecor.fr/>);
- French Research Institute for Exploitation of the Sea (IFREMER, <https://www.ifremer.fr/>);
- International Coral Reef Initiative (ICRI, <http://www.icriforum.org/>);
- International Coral Reef Society (ICRS, <http://coralreefs.org/>);
- LabEx CORAIL (<https://www.labex-corail.fr/>);
- ReefBase—A global information system for coral reefs (<http://www.reefbase.org/>);
- The Endocrine Disruption Exchange (TEDX) List of Potential Endocrine Disruptors (<https://endocrinedisruption.org/interactive-tools/tedx-list-of-potential-endocrine-disruptors>).

Searches were performed between April 21st and May 29th 2020 (Additional file 2).

Call for literature

A call for literature was addressed on July 13th 2020, mainly to the French overseas local authorities (especially

the local French Coral Reef Initiative (IFRECOR) committees), for a total of 18 people contacted.

Assembling and managing search results

The results of all searches were collated and duplicates were automatically removed using the package revtools in the R software [33]. Additional removing of duplicates was done manually with the Microsoft Excel software (duplicate conditional formatting and visual identification). The retrieved records from the searches were processed with the R and Microsoft Excel softwares, and reference management softwares (EndNote and Zotero) were specifically used for searching for full-texts.

Article screening and study eligibility criteria

Screening process

Articles were screened for eligibility in two successive stages: first on titles and abstracts, and second on full-texts. Articles with unclear eligibility status during title/abstract screening were included for full text screening. The list of articles with unclear eligibility status after completion of full-text screening is provided in Additional file 3 with explanation of why they could not be classified. Articles without abstract and retained on the basis of title screening were directly screened on their full-text.

Screening on titles and abstracts was distributed among four reviewers (DYO, LH, RS, YR) and full-text screening among four reviewers as well (DYO, MC, MD, OP). Before the actual screening, all reviewers independently screened a subset of randomly sampled references, and we assessed the consistency between reviewers' decisions by computing the Randolph's Kappa coefficient (Additional file 4). We performed the process in two steps. A first test was done on a small number of references, all disagreements were discussed and the definition of eligibility criteria was further clarified where necessary. Then a second test was performed and all disagreements were again discussed and solved. For titles and abstracts screening a total of 2148/15,177 references (14.2%) were independently screened by all reviewers, and the Randolph's Kappa coefficient was 0.735 for the first test (499 references) and 0.82 for the second test (1649 references). For full-text screening a total of 180/2,700 full-texts (6.7%) were independently screened by all reviewers, and the Randolph's Kappa coefficient was 0.467 for the first test (30 full-texts) and 0.789 for the second test (150 full-texts). During all screening process, we ensured that reviewers never had to screen their own articles.

Eligibility criteria

The eligibility of articles was assessed using the criteria displayed in Table 1. The list of articles rejected at

full-text screening is provided with the reasons for their exclusion in Additional file 3. Reviews and meta-analyses were excluded but those eligible according to the Population-Exposure-Outcome criteria are listed in Additional file 5 to make them easily accessible for possible further use.

Study validity assessment

No critical appraisal of study was performed for the systematic map. Studies were however classified according to whether the exposure was controlled by the researchers (experimental studies) or not (observational studies).

Data coding strategy

All articles included in the map were split into studies, i.e. the combination of a taxon, an exposure, and an outcome, and the following information was recorded in Microsoft Excel sheet from full-texts (details are given in Additional file 6):

- Bibliographic information (unique identifier assigned by the review team, source, title, authors, journal, year, DOI, language and publication type);
- General description of the study (type of study, ISO 3166 country or territory name, latitude and longitude or location);
- Description of the population (taxon and taxon level);
- Description of the exposure (as described by the authors and as an exposure category defined by the review team);
- Description of the type of outcome(s) (as described by the authors and as an outcome category defined by the review team).

The categories of exposure, outcome and type of study defined by the review team are described in Table 2. When corals were simultaneously exposed to several categories of exposure, all of them were indicated (e.g. "Metal | Pesticide").

Data coding was performed by six reviewers (DYO, IDC, KB, MD, MG, RM). Before the actual coding, all reviewers independently coded a random selection of 20/908 articles (2% of all articles, except one of them who coded 10 of the 20 selected articles), all disagreements were discussed, and the coding book (see the first sheet in Additional file 6) was improved where necessary. In case of missing or unclear information, it was coded as such. After completing all the coding, two additional variables were coded from already coded variables. First, the region was determined from the countries following the classification of [34]. Second, the category of chemicals bioaccumulated was determined from the raw exposure

Table 1 Eligibility criteria

Include	Exclude
<p>Population:</p> <ul style="list-style-type: none"> - All tropical reef-building coral species (hermatypic scleractinian species, <i>Millepora</i> species, <i>Heliopora</i> species and <i>Tubipora</i> species) living in the shallow and the mesophotic zones <p>Exposure:</p> <ul style="list-style-type: none"> - All natural (e.g. nitrate), geogenic (e.g. nickel) and synthetic (e.g. diuron) chemicals coming from human activities - Studies assessing the impact of human activities (e.g. river discharge, distance to a dump or to an industrial effluent source, tourism) on corals without reference to a chemical <p>Comparator:</p> <ul style="list-style-type: none"> - Studies comparing population exposed to chemicals and population unexposed to chemicals - Studies comparing population exposed to chemicals and population prior to exposure to chemicals - Studies comparing population exposed to a range of concentrations/ levels of chemicals <p>Outcome:</p> <ul style="list-style-type: none"> - All outcomes related to tropical reef-building corals, from molecular to community level - Studies reporting evidence of ingestion, concentration or accumulation/ uptake of chemicals in the population studied without reporting health consequences - Studies assessing impacts on coral microbiome/symbionts <p>Language:</p> <p>All articles written in English or French (in case a title or an abstract could not be found in English or French, it was directly screened on full-text)</p> <p>Type of document:</p> <p>Journal article, book chapter, report, conference proceeding, PhD or MSc thesis</p> <p>Type of content:</p> <p>In-situ or ex-situ studies</p>	<ul style="list-style-type: none"> - Cold-water or deep-water corals - Ahermatypic corals - Free-living dinoflagellates (not as symbionts in corals) - Studies conducted in coral reefs but not about corals (e.g. about coral reef fishes) <ul style="list-style-type: none"> - Studies assessing the impact of chemicals coming from natural sources (e.g. nutrients from guano) - Studies assessing the impact of organic carbon - Studies assessing the impact of sedimentation per se or impact of physical disturbances on coral - Marine debris, macro-plastics <p>Presentation, editorial material, letter or news item, conference or meeting abstract, poster</p> <p>Reviews and meta-analyses, modelling studies without experimental data</p>

variable. Finally, an attempt was made to identify articles linked to the same experiments (linked articles in the database) and species that have been studied under different names (e.g. *Montastraea annularis* and *Orbicella annularis* are synonyms).

Data mapping method

We produced a database (Microsoft Excel sheet) of all included studies and their coded data (Additional file 6). We mapped the evidence at two levels. First, we described the source, document type, and chronological and geographical distribution of the articles (article level). Then, we described the distribution of studies in taxa, types of exposure and outcome (study level). The description was made separately for experimental and observational studies because whether the exposure was controlled by the researchers (experimental studies)

or not (observational studies) is an important criterion for the subsequent exploitation of the studies. Finally, through the distribution and frequency of studies by types of exposure and/or types of outcomes and/or types of study, we presented four clusters for which a full synthesis of evidence (systematic review) should be possible and relevant for stakeholders, and knowledge gaps.

Review findings

Review descriptive statistics

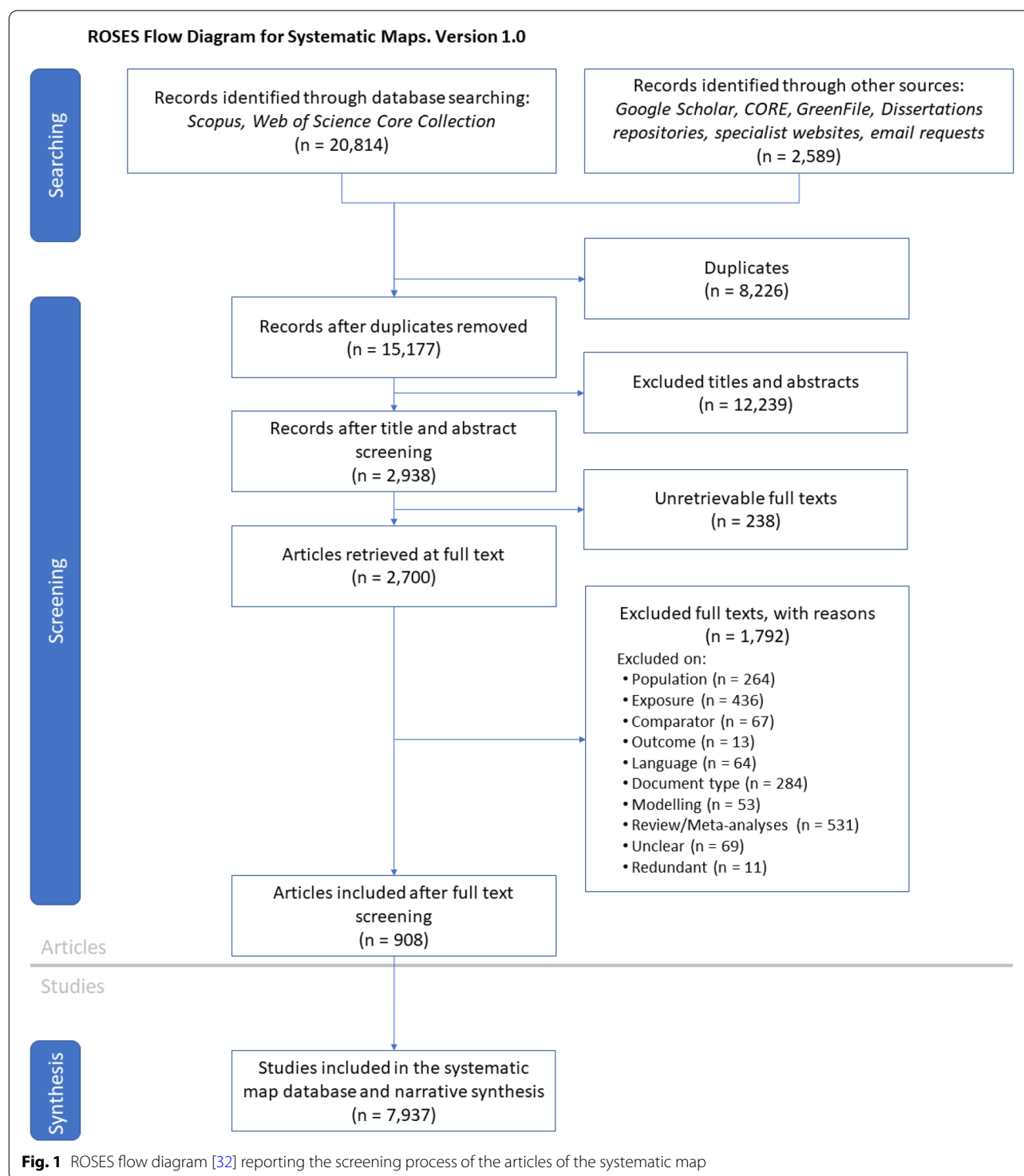
Searches returned 11,342 records from Scopus, and 9,472 records from Web of Science Core Collection. The additional searches gave 400 records from CORE, 1,344 from Google Scholar, 172 from GreenFile, 274 from dissertations repositories, 341 from specialist websites, and 58 from the call for literature (Additional file 2). The whole search gave a total of 23,403 records which resulted in 15,177 articles after duplicate removal (Fig. 1). Among

Table 2 Description of the categories of exposure, outcome and type of study defined by the review team

Categories	Clarifications
Exposure:	
Undefined pollutants	Studies assessing the impact of human activities on corals without reference to a chemical
Nutrient	
Eutrophication	Studies referring to eutrophication without information on the nutrients involved
Metal	
Pesticide	Includes herbicides, fungicides, insecticides, and biocides
Hydrocarbon	Includes crude oil, petroleum, gasoline, diesel, and polycyclic aromatic hydrocarbons
Dispersant	Chemicals used to disperse oil
Detergent	
Microplastic	
Nanoparticle	
Pharmaceutical	
UV filter	
Other	Chemicals that could not be classified elsewhere
Outcome:	
Bioaccumulation	Chemical concentration in the coral
BioaccumulationF	Chemical concentration in the coral when the chemical concentration in the environment is also known (allowing the calculation of a bioaccumulation factor)
Bleaching	
Calcification	Calcification rate, skeletal structure, skeletal density
Coral diversity	Taxa richness, diversity index, taxa composition
Cover	
Disease	
Distribution	Spatial distribution, occurrence
Genetic	Gene expression, population genetic structure
Growth	Skeletal growth, tissue growth, linear extension rate
Microbiome	Outcomes related to the density and characteristics of Symbiodiniaceae and other coral-associated microorganisms
Mortality	
Physiology	Content in carbohydrate, lipid, protein or other biomolecule, enzyme activity, histology, metabolism, mucus production, photopigment concentration, photosynthesis efficiency and other parameters, respiration rates
Recruitment	Settlement success, number of recruits
Reproduction	Fertilisation success, embryo development, state of reproductive structure, planulation
Other	Outcomes that could not be classified elsewhere (e.g. colour change, coral condition, polyp retraction, larval motility)
Type of study:	
Laboratory experiment	Experimental studies (i.e. the exposure was controlled by the researchers) conducted in laboratory conditions
Field experiment	Experimental studies (i.e. the exposure was controlled by the researchers) conducted in the field
Field survey	Observational field studies

them, 2,938 remained after titles and abstracts screening. We could not retrieve 238 full-texts (8%), leaving 2,700 full-text to screen. At full-text screening, articles were mostly excluded because they were reviews/meta-analyses or only synthesizing some findings (29.6%), because of irrelevant exposure (24.3%), irrelevant type of document (15.8%) or irrelevant population (14.7%, Fig. 1). All articles excluded or marked unclear at full-text screening are listed with corresponding reasons in Additional file 3, as well as articles for which we could not retrieve full-text. Among the excluded reviews/meta-analyses,

more than a half (285) were however eligible according to the Population, Exposure, and Outcome criteria; to make them easily accessible for possible further use, they are listed in Additional file 5. At the end of the screening process, a total of 908 articles were found to answer the review question and coded as studies; i.e. the combination of a taxon, an exposure, and an outcome, one article often comprising several studies. Then, the systematic map database comprised 7,937 studies.



Source, document type, chronological and geographical distribution of the articles

The 908 articles included in the systematic map were mainly retrieved from publication databases (85.8%) but specialist websites gave a substantial number of

additional articles (6.5%, Table 3). Articles were mostly written in English (97.8%), and a large portion were journal articles (87.8%), then conference proceedings (5%), PhD, MSc or BSc thesis (3.6%) and reports (3%). The two oldest articles dated back to 1971, and half (49.6%)

Table 3 Proportion of the 908 articles found in the publication databases and then added by supplementary searches with search engines, specialist websites, dissertations repositories, and finally the call for literature

Source	Proportion of the 908 articles
Publication databases (Scopus, Web of Science Core Collection)	85.8%
Search engines (Google Scholar, CORE, GreenFile)	5%
Specialist websites (Reef Base, Ecotox, Coral Trait Database, IFRECOR, AIMS, IFREMER, ICRS, ICRI, Labex Corail)	6.5%
Dissertations repositories (OATD, Theses.fr)	2.6%
Call for literature	0.1%

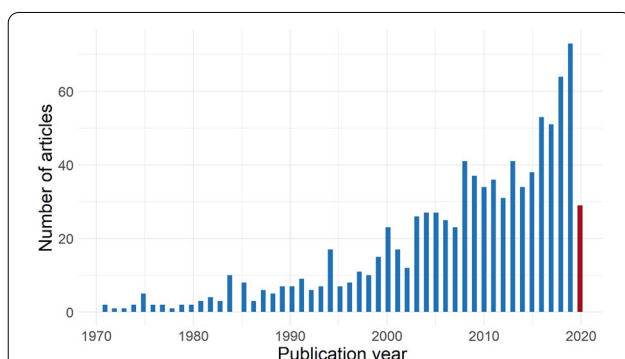


Fig. 2 Chronological distribution of the articles addressing the review question. Because literature search in publication databases were performed in March 2020 this year is incomplete (red bar)

of the articles have been produced since 2010 (Fig. 2). The corals studied were mainly from Southeast Asia (22% of the articles), Australia (13.2%) and Middle Eastern Seas (13.2%, Fig. 3a). It should be noted, however, that if the three Caribbean regions are combined (Eastern Caribbean and Atlantic, Western Caribbean and Northern Caribbean) they become the most represented area with 26.9% of the articles. Corals from the central Indian Ocean were the least studied with only 16 articles (1.7%). At the country/territory level, corals were mainly from the United States of America (13.7% of the articles, mainly Hawaii 8.1% and the Florida Keys 5%), Australia (13.2%), Indonesia (4.9%), China (3.8%), Israel (3.6%), and Japan (3.4%, Fig. 3b). Corals from the French Overseas were studied in 4.4% of the articles, mainly from French Polynesia (10 articles), Réunion (10 articles) and New Caledonia (9 articles).

Description of the studies

Among the 7,937 studies included in the systematic map, roughly half (48.4%) were experimental studies (i.e. the exposure was controlled by the researchers), the experiments being conducted most often in laboratory conditions (39.4%) but also in situ (9%). The remaining studies (51.6%) were observational ones.

Taxa studied

The information on the taxa studied was generally available at the species level (76.1%) or at the genus level (12.6%). A total of 317 taxonomic units (+ the group “reef-building corals”) were recorded, with the most studied species being *Pocillopora damicornis* (9.1% of the studies) and *Stylophora pistillata* (7.6%, Table 4). The taxa studied were different according to the type of study (Table 4). For experimental studies, a total of 148 taxa (+ the group “reef-building corals”) were recorded, mostly at species level (94.7% of the studies), the most studied species being *Pocillopora damicornis* (14.2%), *Stylophora pistillata* (14%), *Acropora muricata* (4%), *Acropora tenuis* (3.8%), *Acropora cervicornis* (3.8%) and *Acropora millepora* (3.6%). For observational studies, a total of 277 taxa (+ the group “reef-building corals”) were recorded but information was available at the species level for only 58.7% of the studies, the group “reef-building corals” being the most studied (12.8%).

The taxa studied were reported in articles spanning almost 50 years (1971–2020). Thus we took into account the latest and on-going revisions of the taxonomy of scleractinians as revealed by molecular phylogeny to update taxon names where needed and possible. For instance, *Madracis auretenra* the shallow-water species name replaced the one of *Madracis mirabilis* (a synonym of *Madracis myriaster*) which develops in deeper water [35]. We made the correction when we could get enough information in the study to distinguish between both names. For the most studied coral *Pocillopora damicornis* which is now recognized as a species complex split into several species including the resurrected *Pocillopora acuta* [36], we could not however distinguish within it.

Exposure

A third of the studies included in the map dealt with the impact of nutrient enrichment (28.4% and 2.1% of the studies in the nutrient and eutrophication categories, respectively), and a quarter (25%) concerned the general impact of human activities on corals, without reference to one or several specific chemical compounds (“Undefined pollutants” category, Table 5). Then, the most studied exposure categories were metal (11.3%), hydrocarbon (7.7%), and pesticide (5.2%). Nutrient enrichment was the first and the second most studied exposure for

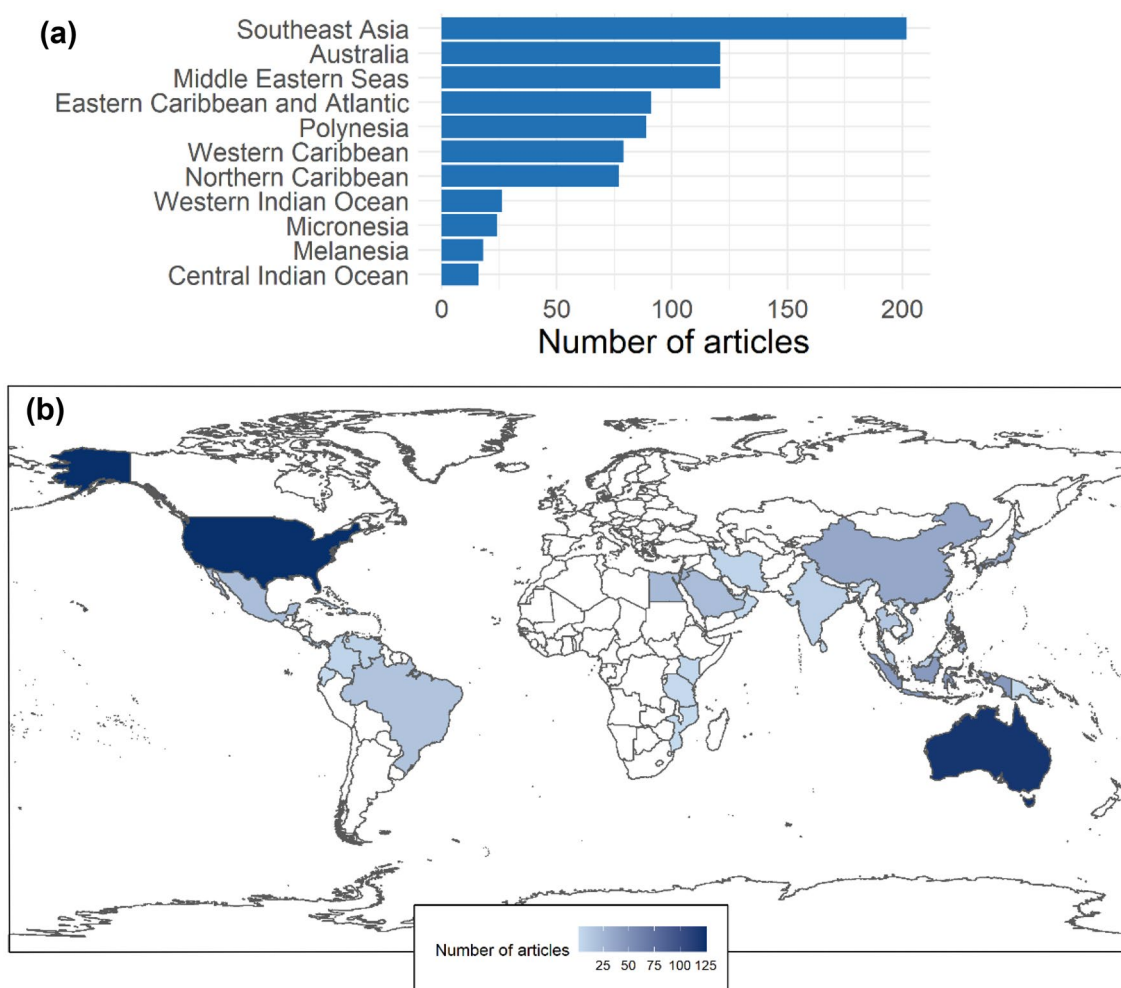


Fig. 3 Geographical distribution of the articles addressing the review question: number of articles by **a** region and **b** country/territory. Articles for which the research was conducted in several countries were not represented

experimental (43%) and observational (18.8%) studies, respectively. Nearly half of the observational studies (47.5%) belonged to the “Undefined pollutants” category. Combinations of three or four categories of exposure could be found in observational studies but never in experimental ones.

Measured outcomes

The most measured outcome was the concentration (or uptake) of chemicals in corals (25.8% of the studies for bioaccumulation and bioaccumulationF, Table 6), followed by outcomes related to coral physiology (16.9%), cover (14%), and mortality (9%). In experimental studies, the most studied outcomes were related to physiology (32.4%), mortality (14.1%), and coral microbiome (11%), whereas in observational studies they were related to chemical concentration in corals (bioaccumulation,

44.4%) and coral cover (26.6%). Outcomes were mainly measured at the colony (51.4% of the studies) and tissue levels (17.9%) (Fig. 4).

Knowledge clusters

Evidence on bioaccumulation of chemicals by corals

A first cluster gathering more than a quarter (25.8%) of the studies in the systematic map measured the concentration (or uptake) of chemicals in corals (2,050 studies for bioaccumulation, Table 6). These studies were mostly observational studies (88.6%) and reported bioaccumulation of metals (74%, Fig. 5). They can thus be the focus of a specific systematic review as they are very numerous, and evidence of bioaccumulation of chemicals is important to know as the entry of contaminants into the cells of organisms is the first step for potential subsequent toxic effects.

Table 4 Total number of studies, experimental studies, and observational studies for the 20 most studied taxa and the group “reef-building corals” (Coral)

Taxa	Total		Experimental		Observational	
<i>Pocillopora damicornis</i>	719	(9.1%)	546	(14.2%)	173	(4.2%)
<i>Stylophora pistillata</i>	603	(7.6%)	537	(14%)	66	(1.6%)
Coral	555	(7%)	33	(0.9%)	522	(12.8%)
<i>Porites</i>	255	(3.2%)	18	(0.5%)	237	(5.8%)
Scleractinia	218	(2.7%)	20	(0.5%)	198	(4.8%)
<i>Acropora tenuis</i>	207	(2.6%)	148	(3.8%)	59	(1.4%)
<i>Acropora muricata</i>	199	(2.5%)	154	(4%)	45	(1.1%)
<i>Porites astreoides</i>	197	(2.5%)	109	(2.8%)	88	(2.2%)
<i>Porites lutea</i>	190	(2.4%)	32	(0.8%)	158	(3.9%)
<i>Acropora</i>	184	(2.3%)	58	(1.5%)	126	(3.1%)
<i>Orbicella annularis</i>	169	(2.1%)	101	(2.6%)	68	(1.7%)
<i>Acropora cervicornis</i>	152	(1.9%)	146	(3.8%)	6	(0.1%)
<i>Acropora millepora</i>	149	(1.9%)	140	(3.6%)	9	(0.2%)
<i>Siderastrea siderea</i>	125	(1.6%)	64	(1.7%)	61	(1.5%)
<i>Pocillopora verrucosa</i>	122	(1.5%)	59	(1.5%)	63	(1.5%)
<i>Porites porites</i>	110	(1.4%)	89	(2.3%)	21	(0.5%)
<i>Porites lobata</i>	105	(1.3%)	34	(0.9%)	71	(1.7%)
<i>Turbinaria reniformis</i>	101	(1.3%)	100	(2.6%)	1	(0%)
<i>Acropora valida</i>	100	(1.3%)	34	(0.9%)	66	(1.6%)
<i>Orbicella faveolata</i>	99	(1.2%)	49	(1.3%)	50	(1.2%)

Evidence on the effects of nutrient enrichment on corals

A second important cluster of studies dealt with coral exposure to nutrient enrichment (2,496 studies about exposure to nutrient or eutrophication). This cluster includes exposure to nutrients in combination with other exposure categories, but excludes studies measuring bioaccumulation. Coral exposure to nutrients was highly studied, through both experiments (64.6% of the studies) and field observations (35.4%, Fig. 6). Coral physiology (31.5% of the studies) and cover (18.3%) were the most studied outcomes, mainly through experiments and observational studies, respectively. The effects of nutrient exposure on corals can be the focus of a large systematic review, but given the high number of studies, focusing on some specific outcomes and/or type of study may be relevant.

Evidence on the effects of human activities on corals without reference to chemicals

A third cluster of studies (1,127 studies) dealt with the impact of human activities on corals without reference to a chemical (“Undefined pollutants” category). The cluster defined here excludes studies measuring bioaccumulation. These studies were mainly observational (96.9%). Among these studies, the outcomes most often studied were coral cover (48.2%), mortality (10.2%), and disease (10.1%, Fig. 7). Because these studies provided

no information on the chemicals that may explain the observed effects on corals, they should be synthesized separately, and can therefore be the focus of a systematic review indicating how various human activities (e.g. urbanisation, tourism, agriculture, industries) impact corals. The review could also focus on the impact of human activities on coral cover as this represents a large cluster of 543 studies.

Evidence on the ecotoxicological effects of chemicals on corals

A fourth large cluster of studies (2,007 studies) gathered evidence of experimental studies on the effects of chemicals on corals. The cluster defined here excludes studies measuring bioaccumulation, exposure to unknown chemicals (“Undefined pollutants” category) and exposure to nutrient or eutrophication. Exposure to metals (21%), hydrocarbons (19.8%), and pesticides (19.6%) were the most studied (Fig. 8). Some exposure categories were only recently studied: since 2008 for UV filters, 2014 for nanoparticles and detergents, and 2017 for microplastics. Outcomes related to coral physiology, mortality, microbiome, reproduction, recruitment and growth were studied for nearly all exposure categories (Fig. 8). A systematic review comparing the relative effects of the different exposure categories on these outcomes is therefore possible.

Table 5 Total number of studies, experimental studies, and observational studies by exposure category. Vertical bars separate simultaneous exposure to several categories

Exposure category	Total		Experimental		Observational	
Undefined pollutants	1986	(25%)	41	(1.1%)	1945	(47.5%)
Nutrient	2255	(28.4%)	1645	(42.8%)	610	(14.9%)
Eutrophication	168	(2.1%)	7	(0.2%)	161	(3.9%)
Metal	896	(11.3%)	497	(12.9%)	399	(9.8%)
Hydrocarbon	608	(7.7%)	401	(10.4%)	207	(5.1%)
Pesticide	416	(5.2%)	396	(10.3%)	20	(0.5%)
UV filter	209	(2.6%)	184	(4.8%)	25	(0.6%)
Microplastic	134	(1.7%)	132	(3.4%)	2	(0%)
Pharmaceutical	112	(1.4%)	112	(2.9%)	–	
Dispersant	61	(0.8%)	61	(1.6%)	–	
Detergent	21	(0.3%)	21	(0.5%)	–	
Nanoparticle	15	(0.2%)	15	(0.4%)	–	
Other	114	(1.4%)	102	(2.7%)	12	(0.3%)
Metal Nutrient	290	(3.7%)	44	(1.1%)	246	(6%)
Metal Pesticide	15	(0.2%)	15	(0.4%)	–	
Metal Hydrocarbon	15	(0.2%)	3	(0.1%)	12	(0.3%)
Metal Other	5	(0.1%)	–		5	(0.1%)
Metal Pharmaceutical	1	(0%)	1	(0%)	–	
Hydrocarbon Dispersant	166	(2.1%)	166	(4.3%)	–	
Hydrocarbon Other	90	(1.1%)	–		90	(2.2%)
Hydrocarbon Nutrient	15	(0.2%)	1	(0%)	14	(0.3%)
Hydrocarbon Pharmaceutical	1	(0%)	1	(0%)	–	
Nutrient Hydrocarbon Metal	192	(2.4%)	–		192	(4.7%)
Pharmaceutical Nutrient Metal	19	(0.2%)	–		19	(0.5%)
Nutrient Hydrocarbon Other	6	(0.1%)	–		6	(0.1%)
Nutrient Hydrocarbon Pesticide	2	(0%)	–		2	(0%)
Hydrocarbon Pesticide Other	1	(0%)	–		1	(0%)
Nutrient Hydrocarbon Metal Other	61	(0.8%)	–		61	(1.5%)
Hydrocarbon Pesticide Metal Other	34	(0.4%)	–		34	(0.8%)
Nutrient Pesticide Detergent Hydrocarbon	18	(0.2%)	–		18	(0.4%)
UV filter Hydrocarbon Pharmaceutical Other	11	(0.1%)	–		11	(0.3%)
Total	7937		3845		4092	

Knowledge gaps

Geographical regions

The central (124 studies) and western Indian Ocean (215), Micronesia (96) and Melanesia (222) where the less studied areas, and most of the studies in these areas were observational (71.8%).

Population

Among the 317 taxonomic units recorded in the map, 147 were represented by less than five studies. At family level, the two least studied families (with less than five studies) were the Oulastreidae and the Rhizangiidae families.

Exposure

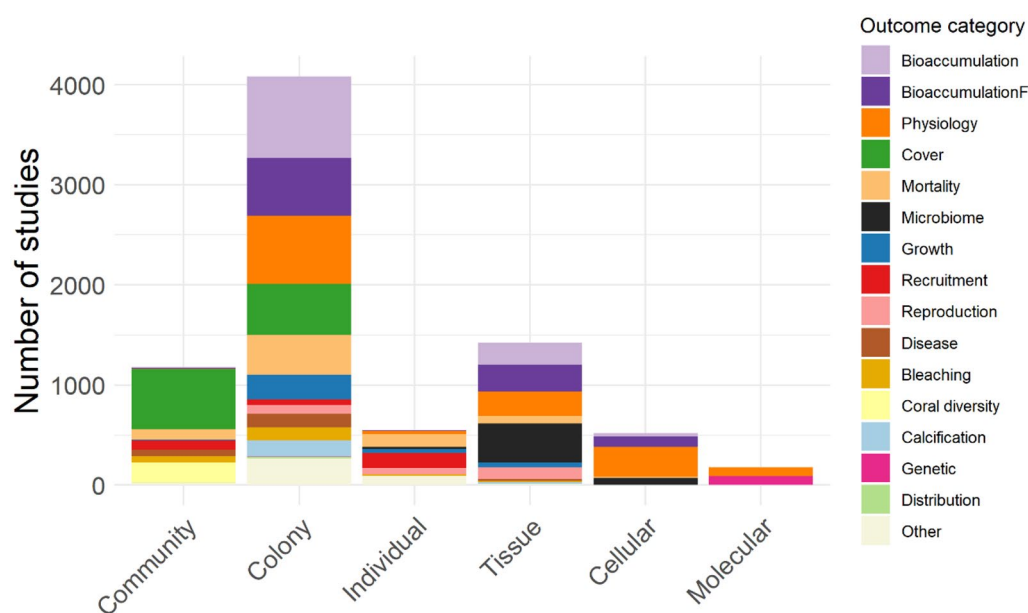
Exposure to nanoparticles (15 studies) and detergents (21) were the least studied (Table 5). Some combinations of categories of exposure were also hardly studied (see Table 5) and combinations of three or four categories of exposure were never studied experimentally.

Outcomes

The least studied outcomes were those related to the distribution (occurrence) and genetics of corals (Table 6). For coral distribution, this information may however be extracted from coral cover, which is the second most studied outcome in observational studies, thus we may consider that this is not entirely a knowledge gap. For

Table 6 Total number of studies, experimental studies, and observational studies by outcome category

Outcome category	Total		Experimental		Observational	
Bioaccumulation	1082	(13.6%)	11	(0.3%)	1071	(26.2%)
BioaccumulationF	968	(12.2%)	222	(5.8%)	746	(18.2%)
Physiology	1344	(16.9%)	1247	(32.4%)	97	(2.4%)
Cover	1113	(14%)	24	(0.6%)	1089	(26.6%)
Mortality	716	(9%)	543	(14.1%)	173	(4.2%)
Microbiome	483	(6.1%)	424	(11%)	59	(1.4%)
Growth	339	(4.3%)	264	(6.9%)	75	(1.8%)
Recruitment	302	(3.8%)	161	(4.2%)	141	(3.4%)
Reproduction	271	(3.4%)	189	(4.9%)	82	(2%)
Disease	219	(2.8%)	44	(1.1%)	175	(4.3%)
Bleaching	215	(2.7%)	145	(3.8%)	70	(1.7%)
Coral diversity	203	(2.6%)	1	(0%)	202	(4.9%)
Calcification	185	(2.3%)	155	(4%)	30	(0.7%)
Genetic	90	(1.1%)	78	(2%)	12	(0.3%)
Distribution	15	(0.2%)	–		15	(0.4%)
Other	392	(4.9%)	337	(8.8%)	55	(1.3%)

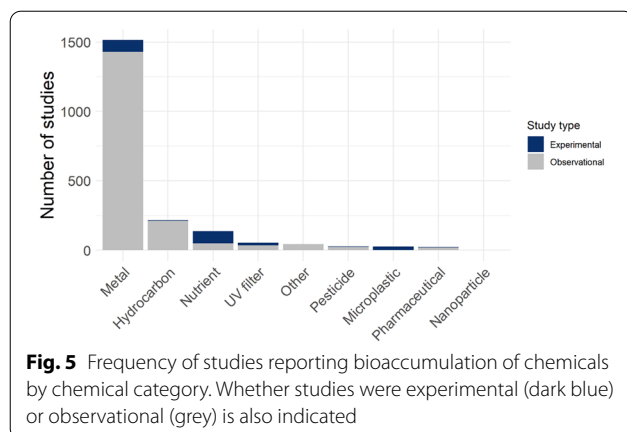

Fig. 4 Number of studies by outcome level and category. Here, the “colony” level refers to the set of connected individual polyps (colony *stricto sensu*) or to a set of several colonies of the same species

genetics, only two (observational) studies relate to the genetic structure of populations, and the other ones (88 studies, 78 being experimental) relate to gene expression or DNA damage. Because the ability to measure genetic outcomes improve with time and technological development, we expect that much more evidence on genetic outcomes may be available in the coming years.

Limitations of the map

Limitations of the synthesis method

Firstly, we found a high number of syntheses/reviews/meta-analyses that met our eligibility criteria (285 articles listed in Additional file 5). They may contain a substantial number of references that were not retrieved by our literature searches. For instance, 19% of the articles in the systematic map of Sordello et al. [37] came



from snowballing the bibliography of relevant reviews. Extracting references from these reviews and screening them was not possible here due to time constraints, but this could be done by others in the future.

Secondly, the search was conducted in English only, and the evidence was limited to English and French literature (the languages understood by the review team), although it likely exists in other languages [38]. This may have resulted in less geographical coverage of the map and an under-representation of countries where English is not widely spoken or where the scientific literature is also widely published in non-English language (e.g. China, Japan). During the screening process, we excluded 64 articles due to language which are listed in Additional

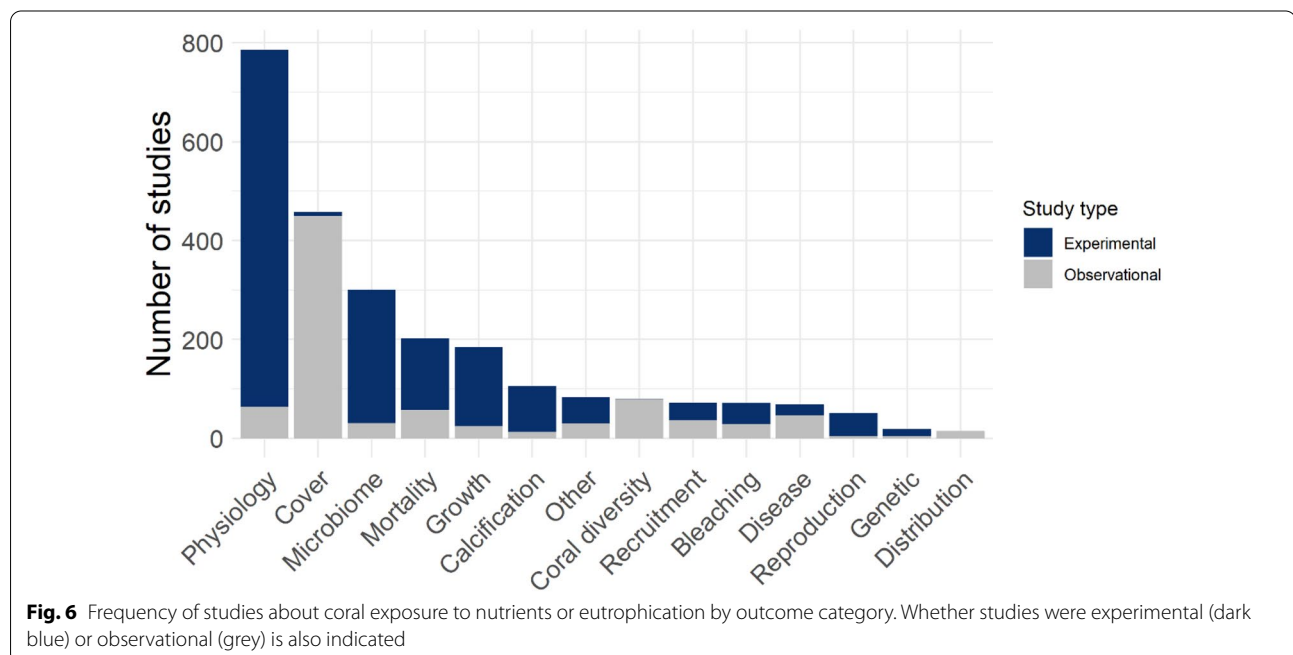
file 3 and could be screened for eligibility and used by others.

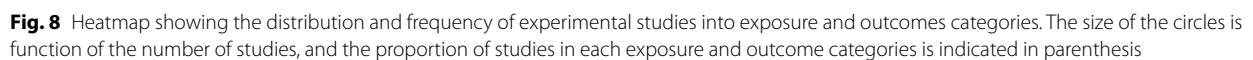
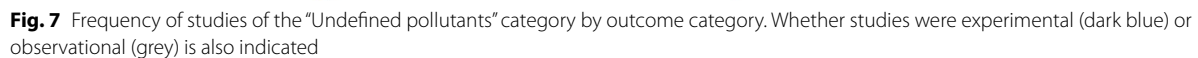
Thirdly, some of the outcome categories defined by the review team were very broad and gathered very different outcomes (e.g. the outcome “physiology” may refer to either photosynthetic efficiency, enzyme activity, or mucus production). For these broad categories, defining more specific outcome categories may be necessary before conducting syntheses; this could be done directly from the map database using the detailed raw description of the outcomes.

Finally, considering exposure to nutrients and according to our eligibility criteria we included nutrient enrichment arising from human activities but we excluded natural nutrient enrichment (stemming from guano, or upwelling). Although effects are likely similar, exposure to natural nutrient enrichment is thus not considered in this systematic map.

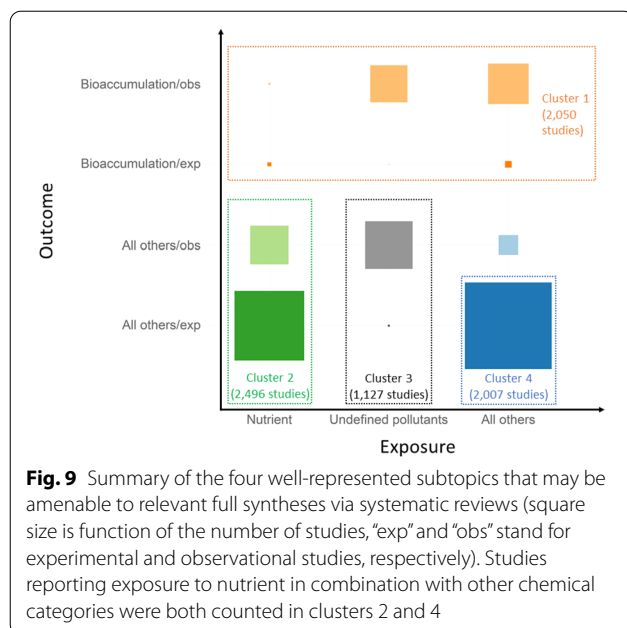
Limitations of the evidence base

The systematic map revealed some mismatch between the amount of literature available on the impact of chemicals on corals from a country and the coral reef area of that country. For example, corals from the United States of America (mainly Hawaii and the Florida Keys) were the most studied (13.7% of the articles) while the United States are only 16th in the world in terms of reef area (1.3% of the world's total coral reef area, [29]). In contrast, the Philippines is ranked third in the world in terms of reef area (9% of the world's total coral reef area, [29])





systematic map at all (Solomon Islands, Vanuatu, Eritrea, Sudan, [29]). This could be due to a lack of studies for these countries, to studies being available mainly in



the form of grey literature difficult to access, or to articles being published in non-English languages.

Conclusions

This systematic map gathered evidence on the impact of chemicals arising from human activities on tropical reef-building corals. The topic is very large as demonstrated by the abundant scientific literature found (908 articles, 7,937 studies). We identified four well-represented subtopics that may be amenable to relevant full syntheses via systematic reviews (Fig. 9): (1) evidence on bioaccumulation of chemicals by corals; (2) evidence on the effects of nutrient enrichment on corals; (3) evidence on the effects of human activities on corals; and (4) evidence on the ecotoxicological effects of chemicals (except nutrients) on corals.

Implication for policy/management

This structured compilation of all available literature will help guide decision-makers on which clusters to focus on, in a regulatory context, and which priority research topics to support in the future. In addition, one way for decision-makers to take action for coral reef protection from chemicals is to assess risk, which is the result of chemical toxicity and exposure. From the map, it will be possible to extract evidence of toxicity from experimental studies, and exposure data from observational studies. Finally, this systematic map can help local stakeholders identify the body of literature that is relevant to their particular concern. For instance, if local stakeholders are concerned with the impact of nickel mining on corals,

they will be able to easily search the map database under the metal exposure category and select studies relevant to their issue.

Implication for research

From the results of our systematic map, we were able to distinguish a group of well-studied pollutants (nutrient, metal, hydrocarbon and pesticide) and another group that has been more recently studied (nanoparticles, detergents, microplastics and UV filters) which thus shows fewer available studies at this time. We can expect that the research effort on these pollutants will continue to increase, and that much more evidence will be available in the coming years. In addition, we identified experimental studies assessing the combined effect of different categories of pollutants (e.g. metal and nutrient) but never more than two categories at a time. We also identified observational studies reporting exposure to three or four different categories of pollutants (e.g. nutrient, pesticide, detergent and hydrocarbon). This confirms that corals in their natural environment are exposed to many different categories of chemicals, possibly interacting with one another (i.e. mixture effects) and that there is a lack of experimental evidence for the combined effects of more than two categories of chemicals. We therefore encourage research on this topic.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s13750-021-00237-9>.

Additional file 1: ROSES for systematic map reports checklist. ROSES form for systematic map reports version 1.0.

Additional file 2: Summary of literature searches. Summary of all the searches for literature with dates of search and number of articles found.

Additional file 3: List of excluded articles. List of the articles with missing full-texts, excluded or marked as unclear.

Additional file 4: List of references used for screening consistency checking. List of the references used for checking the consistency of screening decisions.

Additional file 5: List of eligible syntheses. List of the eligible syntheses/reviews/meta-analyses.

Additional file 6: Map database. List of the 908 articles answering the review question and database of the 7,937 studies included in the map with coded variables.

Acknowledgements

The authors would like to thank Nicolas Da Rocha for his help during the search for full-texts. We are also grateful to Omar Alaoui (TAAF), Jean-Pierre Allenou, Magali Duval and Emilie Gauthier (Ifremer), Jimmy Le Bec (DEAL Guadeloupe), Corinne Caroff and Nicolas Tamic (CEDRE), Clément Lelabousse (OFB), and Pascal Talec (DEAL Réunion) for the information, contacts and/or articles they provided during the call for literature.

Authors' contributions

DYO undertook the searches; DYO, LH, RS and YR screened titles and abstracts; DYO and CL searches for full-texts; DYO, MC, MD and OP screened full-texts; DYO, IDC, KB, MD, MG, and RM made the coding of studies. This report is based on a draft written by DYO. All authors read, commented and approved the final manuscript.

Funding

This map was funded by the French Office for Biodiversity (OFB) and the French National Museum of Natural History (MNHN).

Availability of data and materials

All data generated or analysed during this study are included in this published article and its supplementary information files.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

In 2018, CFP collaborated with the private company "L'Oréal" for a research work on the impact of sunscreen ingredients on a coral species. LH is currently conducting research on the effects of cosmetic ingredients on young stages of corals of French Polynesia for the private company "Comptoir du Monoï".

Author details

¹Direction de L'Expertise, Muséum National d'Histoire Naturelle (MNHN), 75005 Paris, France. ²UMS PatriNat, OFB, MNHN, CNRS, 75005 Paris, France. ³Laboratoire d'Excellence CORAIL, 66860 Perpignan, France. ⁴USR 3278 CRILOBE, PSL Université Paris: EPHE, UPVD, CNRS, 98729 Papetoai, Moorea, French Polynesia. ⁵Institut de Systématique, Evolution, Biodiversité (ISYEB), Muséum National d'Histoire Naturelle, CNRS, Sorbonne Université, EPHE, Université Des Antilles, 75005 Paris, France. ⁶Office Français de La Biodiversité (OFB), 94300 Vincennes, France. ⁷Laboratoire Molécules de Communication Et Adaptation Des Microorganismes (MCAM) UMR 7245, CNRS, Muséum National d'Histoire Naturelle (MNHN), 75005 Paris, France. ⁸French Agency for Food, Environmental and Occupational Health & Safety (ANSES), 94701 Maisons-Alfort Cedex, France. ⁹Equipe Ecophysiologie Corallienne, Centre Scientifique de Monaco, 8 Quai Antoine 1er MC-98000, Monaco. ¹⁰Laboratoire de Biologie Des Organismes Et Ecosystèmes Aquatiques (BOREA), Muséum National d'Histoire Naturelle, CNRS, SU, IRD, UCN, UA EcoFunc, Aviv, 75005 Paris, France. ¹¹Service Recherche, enseignement, expertise, Bibliothèque centrale, DGD C, Muséum National d'Histoire Naturelle (MNHN), 75005 Paris, France. ¹²Biocapteurs Analyses Environnement, University of Perpignan Via Domitia, 66000 Perpignan, France. ¹³Laboratoire de Biodiversité Et Biotechnologies Microbiennes (LBBM), Sorbonne Universités, CNRS, 66650 Banyuls sur Mer, France. ¹⁴Direction du Pôle Expéditions, DGD C, Muséum National d'Histoire Naturelle (MNHN), 75005 Paris, France.

Received: 30 April 2021 Accepted: 6 September 2021

Published online: 22 September 2021

References

- Hoeksema BW. The hidden biodiversity of tropical coral reefs. *Biodiversity* Taylor & Francis. 2017;18:8–12.
- Burke L, Reyter K, Spalding M, Perry A. Reefs at risk revisited. Washington DC: World Resources Institute; 2011.
- Ferrario F, Beck MW, Storlazzi CD, Micheli F, Shepard CC, Airoldi L. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nat Commun*. 2014;5:1–9.
- Barlow J, França F, Gardner TA, Hicks CC, Lennox GD, Berenguer E, et al. The future of hyperdiverse tropical ecosystems. *Nature*. 2018;559:517–26.
- Ellis JI, Jamil T, Anlauf H, Coker DJ, Curdia J, Hewitt J, et al. Multiple stressor effects on coral reef ecosystems. *Glob Change Biol*. 2019;25:4131–46.
- Hoegh-Guldberg O, Poloczanska ES, Skirving W, Dove S. Coral reef ecosystems under climate change and ocean acidification. *Front Mar Sci*. 2017;4:158.
- Hoegh-Guldberg O, Pendleton L, Kaup A. People and the changing nature of coral reefs. *Reg Stud Mar Sci*. 2019;30:100699.
- Wilkinson C. Status of coral reefs of the world: 2008. Townsville: Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre; 2008.
- Donovan MK, Adam TC, Shantz AA, Speare KE, Munsterman KS, Rice MM, et al. Nitrogen pollution interacts with heat stress to increase coral bleaching across the seascape. *Proc Natl Acad Sci*. 2020;117:5351–7.
- MacNeil MA, Mellin C, Matthews S, Wolff NH, McClanahan TR, Devlin M, et al. Water quality mediates resilience on the Great Barrier Reef. *Nat Ecol Evol*. 2019;3:620–7.
- Schuhmacher H, Zibrowius H. What is hermatypic? *Coral Reefs*. 1985;4:1–9.
- LaJeunesse TC, Parkinson JE, Gabrielson PW, Jeong HJ, Reimer JD, Voolstra CR, et al. Systematic revision of symbiodiniaceae highlights the antiquity and diversity of coral endosymbionts. *Curr Biol*. 2018;28:2570–2580.e6.
- Muscattine L. The role of symbiotic algae in carbon and energy flux in reef corals. In: Dubinsky Z, editor. *Coral reefs*. Elsevier: Amsterdam; 1990. p. 75–87.
- Tremblay P, Grover R, Maguer JF, Legendre L, Ferrier-Pages C. Autotrophic carbon budget in coral tissue: a new 13C-based model of photosynthate translocation. *J Exp Biol*. 2012;215:1384–93.
- Wilkinson CR. Global and local threats to coral reef functioning and existence: review and predictions. *Mar Freshw Res*. 1999;50:867–78.
- Duprey NN, Yasuhara M, Baker DM. Reefs of tomorrow: eutrophication reduces coral biodiversity in an urbanized seascape. *Glob Change Biol*. 2016;22:3550–65.
- DeCarlo TM, Cohen AL, Barkley HC, Cobban Q, Young C, Shamberger KE, et al. Coral macrobioerosion is accelerated by ocean acidification and nutrients. *Geol GeoScienceWorld*. 2015;43:7–10.
- Wooldridge SA. Water quality and coral bleaching thresholds: formalising the linkage for the inshore reefs of the Great Barrier Reef, Australia. *Mar Pollut Bull*. 2009;58:745–51.
- De Barros Marangoni LF, Marques JA, Duarte GAS, Pereira CM, Calderon EN, e Castro CB, et al. Copper effects on biomarkers associated with photosynthesis, oxidative status and calcification in the Brazilian coral *Mussismilia harttii* (Scleractinia, Mussidae). *Mar Environ Res*. 2017;130:248–57.
- Prouty NG, Cohen A, Yates KK, Storlazzi CD, Swarzenski PW, White D. Vulnerability of coral reefs to bioerosion from land-based sources of pollution. *J Geophys Res Oceans*. 2017;122:9319–31.
- Richmond RH, Tisthammer KH, Spies NP. The effects of anthropogenic stressors on reproduction and recruitment of corals and reef organisms. *Front Mar Sci*. 2018;5:226.
- Dubinsky ZVY, Stambler N. Marine pollution and coral reefs. *Glob Change Biol*. 1996;2:511–26.
- van Dam JW, Negri AP, Uthicke S, Mueller JF. Chapter 9: Chemical Pollution on Coral Reefs: Exposure and Ecological Effects. *Ecological Impacts of Toxic Chemicals*. 2011. p. 187–211.
- D'Angelo C, Wiedenmann J. Impacts of nutrient enrichment on coral reefs: new perspectives and implications for coastal management and reef survival. *Curr Opin Environ Sustain*. 2014;7:82–93.
- Jones R. The ecotoxicological effects of Photosystem II herbicides on corals. *Mar Pollut Bull*. 2005;51:495–506.
- Haapkyla J, Ramade F, Salvat B. Oil pollution on coral reefs: a review of the state of knowledge and management needs. *Vie Milieu-Life Environ*. 2007;57:95–111.
- Wood E. Impacts of sunscreens on coral reefs. *International Coral Reef Initiative (ICRI)*; 2018. p. 20.
- Joannot P. Les récifs coralliens, un écosystème à protéger. *Sci Au Présent* 2010. *Encyclopedia Universalis*; 2010. p. 204–14.
- Sheppard C, Davy S, Pilling G, Graham N. Coral reefs: biodiverse and productive tropical ecosystems. In: *Biological coral reefs*, 2nd edn. Oxford: Oxford University Press; 2018.
- Collaboration for Environmental Evidence. Guidelines and standards for evidence synthesis in environmental management. Version 5.0 (Pullin AS, Frampton GK, Livoreil B, Petrokofsky G, editors) www.environmentalevidence.org/information-for-authors. Accessed 12 Nov 2019. [Internet].

- Pullin A, Frampton G, Livoreil B, Petrokofsky G, editors. 2018 [cited 2019 Nov 12]. www.environmentalevidence.org/information-for-authors.
31. Ouédraogo D-Y, Sordello R, Brugneaux S, Burga K, Calvayrac C, Castelin M, et al. What evidence exists on the impacts of chemicals arising from human activity on tropical reef-building corals? A systematic map protocol. *Environ Evid*. 2020;9:18.
 32. Haddaway N, Macura B, Whaley P, Pullin A. ROSES flow diagram for systematic maps. Version 1.0. 2017;
 33. Westgate MJ. revtools: an R package to support article screening for evidence synthesis. *Res Synth Methods*. 2019;10:606–14.
 34. Spalding MD, Ravilious C, Green EP. World atlas of coral reefs. University of California Press ; 2001.
 35. Locke JM, Weil E, Coates KA. A newly documented species of *Madracis* (Scleractinia: Pocilloporidae) from the Caribbean. *Proc Biol Soc Wash*. 2007;120:214–26.
 36. Schmidt-Roach S, Miller KJ, Lundgren P, Andreakis N. With eyes wide open: a revision of species within and closely related to the *Pocillopora damicornis* species complex (Scleractinia; Pocilloporidae) using morphology and genetics: *Pocillopora* Species. *Zool J Linn Soc*. 2014;170:1–33.
 37. Sordello R, Ratel O, Flamerie De Lachapelle F, Leger C, Dambry A, Vanpeene S. Evidence of the impact of noise pollution on biodiversity: a systematic map. *Environ Evid*. 2020;9:20.
 38. Amano T, Espinola VB, Christie AP, Willott K, Akasaka M, Baldi A, et al. Tapping into non-English-language science for the conservation of global biodiversity. *bioRxiv*. Cold Spring Harbor Laboratory; 2021;2021.05.24.445520.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Ready to submit your research? Choose BMC and benefit from:

- fast, convenient online submission
- thorough peer review by experienced researchers in your field
- rapid publication on acceptance
- support for research data, including large and complex data types
- gold Open Access which fosters wider collaboration and increased citations
- maximum visibility for your research: over 100M website views per year

At BMC, research is always in progress.

Learn more biomedcentral.com/submissions

