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Societal impacts of marine nitrogen pollution: rapid evidence assessment and future research

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Nitrogen pollution is a global problem and to effectively mitigate the effects we need to understand both the ecological and societal impacts. Coral reefs are of particular concern, as they are a critical source of livelihoods, culture, and wellbeing for hundreds of millions of people. Yet they are rapidly declining due to numerous pressures, with nitrogen pollution identified as a top-ranked non-climatic pressure. A Rapid Evidence Assessment was carried out to understand the societal impacts derived from marine nitrogen pollution on coral reefs. The results highlight key research evidence gaps, such as unclear reporting of nitrogen pollution, not distinguishing impacts from nitrogen and other stressors, non-quantification of nitrogen-specific marine and societal impacts, unstudied global regions with high nitrogen pressure, and the need for greater awareness on marine nitrogen pollution. Future research questions are proposed to allow better understanding on how tropical coastal societies are being impacted by marine nitrogen pollution.

KEYWORDS

coral reef, ecosystem service, eutrophication, marine pollution, nitrogen, society

1 Introduction

Tackling the many regional nitrogen boundaries that we have exceeded is a critical global challenge that exacerbates other planetary boundaries such as climate change and ozone depletion (Steffen et al., 2015; Schulte-Uebbing et al., 2022). Nitrogen excess or pollution from sources such as sewage, burning fossil fuels, agriculture fertilizers, and others is degrading air and water quality, which then affects ecosystem and human health, biodiversity, and livelihoods (Sutton et al., 2021). Despite multiple nitrogen-relevant UN agencies and conventions since 1972 (e.g., Resolution on Sustainable Nitrogen Management, during the Fourth Session of the UN Environment Assembly 2019; UN Global Campaign on Sustainable nitrogen Management 2019), global levels of nitrogen pollution have increased, tripling in magnitude over the last five decades (Sutton et al., 2021). However, there is now global momentum for an ambitious halving of nitrogen waste by 2030 (e.g., Colombo Declaration 2019; Target 7 of the Kunming-Montreal Global Biodiversity Framework).

To effectively mitigate excess nitrogen impacts, it is crucial to characterize the nature of nitrogen sources, the magnitude and spatial variability of nitrogen inputs, and the impacts on ecosystem services valued by society (Keeler et al., 2016). Understanding the broader implications of nitrogen pollution, beyond the ecological impacts, is a key to forming and guiding future policy (Sutton et al., 2021). Evidencing the social and economic impacts, for example through ecosystem service assessments, provides a solid case for intervention and can enable the targeting of effective policies to reduce these impacts. Research to determine these broader impacts still in its infancy but if the issue of nitrogen pollution is to be efficiently tackled, maximizing benefits to society is a key research area.

Several efforts worldwide have attempted to assess the damage costs caused by excessive nitrogen loads (e.g., Brink et al., 2011; Compton et al., 2011; Gu et al., 2015; Keeler et al., 2016; van Grinsven et al., 2018). However, most of these efforts have focused on terrestrial ecosystems and limited natural marine habitats (e.g., Moksnes et al., 2021). To the best of our knowledge, this is one of the first studies that focuses on the implications of nitrogen loads on coastal and marine ecosystem services and people, particularly coral reef ecosystems.

Coral reefs are among the most diverse marine ecosystems on the planet and a critical source of livelihoods, culture, wellbeing, coastal protection, and food security for hundreds of millions of people. However, global and local pressures are causing rapid declines in coral ecosystem health, with global coverage of living coral having declined by half since the 1950s (Eddy et al., 2021). More recently, the global average coral cover declined several times between 2005 and 2019. These declines suggest an average loss of 14% (Souter et al., 2021). Andrello et al. (2022) found that water pollution (sediments and nitrogen) and fishing were the most frequently top-ranked non-climatic pressure on 63.1% of the world's coral reefs. Water pollution was the top-ranked pressure in 32.3% for all reefs, yet with extremes in regional variation, from 1.4% of reefs in Micronesia to 47.9% of reefs in Melanesia. Further, coastal population pressure can also have water pollution impacts; for example, from wastewater and storm water run-off, suggesting water pollution may be an even greater pressure on coral reefs than previously estimated (Burke et al., 2011).

Water pollution, specifically nitrogen pollution, reaches coral reefs mainly from sewage, industrial effluents, and agriculture runoff (Robin et al., 2013; Karthik et al., 2020). The impacts of water pollution and other stressors on coral reefs are complex, varied and often synergistic (Crisp et al., 2022). The impacts of nitrogen pollution can often be evidenced by shifts from coral to macroalgae- or sea urchin dominance shifts (Bruno et al., 2009; Norström et al., 2009) but can range from bioerosion and crown-of-thorn infestations to prevalence of coral diseases and lowered resistance to ocean acidification (Painter et al., 2023).

With continued degradation of coral reefs and associated loss of biodiversity and fishery catches, the wellbeing and sustainable coastal development of human communities that depend on coral reef ecosystem services are threatened. Coral reefs provide many ecosystem services to society, such as food provision, tourism and recreation, coastal protection, and contributions to culture (Kermagoret et al., 2019). The value of ecosystem services provided by coral reefs is estimated at US$2.7 trillion per year, including US$36 billion in coral reef tourism (Souter et al., 2021). However, Eddy et al. (2021) found that the capacity of global coral reefs to provide ecosystem services has declined by half since the 1950s. Maintaining the integrity and resilience of coral reef ecosystems is essential for the wellbeing of tropical coastal communities worldwide, and a critical part of the solution for achieving the Sustainable Development Goals (SDG) under the 2030 Agenda for Sustainable Development (Souter et al., 2021). More specifically, the global community has identified the importance of ecosystem services provided by coral reefs through its commitment to achieve targets associated with SDG2 (end hunger, achieve food security, improved nutrition, and promote sustainable agriculture) and SDG14 (conserve and sustainably use the oceans, seas, and marine resources for sustainable development; particularly reducing export of silt and nutrient pollution to coastal waters-SDG14.1; Eddy et al., 2021). Understanding the impacts of nitrogen pollution on coral reefs" capacity to provide ecosystem services is vital for ensuring a sustainable blue economy, establishing recovery targets, achieving the United Nations SDGs, and anticipating where and how current and future societies will be impacted and to what extent.

The goal of this paper is to review the state of the science connecting marine nitrogen pollution impacts with impacts on society, by addressing the following specific research questions: (i) Which ecosystem services are directly or indirectly impacted by nitrogen pollution in coral reefs? (ii) What groups of actors are impacted by nitrogen pollution on coral reefs? (iii) Which methods have been used to qualify or quantify the impacts? (iv) What areas of research need to be advanced for increased understanding of the effects of marine nitrogen pollution on people?

This paper is structured as follows. Section 2 explains the Rapid Evidence Assessment (REA) methodology and its application, and selection of objects of study. Section 3 presents the results of the REA by first setting the scene with a description of selected papers and then reviewing findings from marine nitrogen indicators and sources to ecosystem services and nitrogen abatement measures. Finally, section 4 highlights the key evidence gaps in the literature and discusses recommendations for future research needed to advance the understanding on the impacts of marine nitrogen pollution on ecosystem services and thus to society.

2 Methodology: rapid evidence assessment

A rapid evidence assessment (REA) was applied to cover relevant knowledge from the existing literature. "*A rapid review is a form of knowledge synthesis that accelerates the process of conducting a traditional systematic review through streamlining or omitting specific methods...*" (Garritty et al., 2020, p. 2). REAs are increasingly preferred as an alternative to systematic reviews, especially in time and resource restricted settings (Varker et al., 2015). Through a detailed evaluation of existing conceptual, theoretical, modeling, and empirical studies, REA can explore the understanding to date on how marine nitrogen pollution impacts society. The objective of the REA was to synthesize findings from the existing literature on what direct or indirect effects nitrogen pollution on coral reef ecosystems has on the different ecosystem services that society receives from the marine-coastal environment. Given that the links between nitrogen pollution, coral reefs and other marine habitats, and the provision of ecosystem services has proven to be empirically challenging, literature explicitly studying these linkages has only emerged recently. Nevertheless, given the abundant studies on the impacts of nitrogen pollution on marine-coastal environments (e.g., Tuholske et al., 2021) and the conceptual links between marine-coastal environments and ecosystem services (e.g., Hattam et al., 2015; Villasante et al., 2016; Carrasco de la Cruz, 2021), we propose that research which could underpin and provide a better understanding of the quantification, qualification and valuation of the impacts of marine nitrogen pollution is likely to exist.

2.1 Search design

To ensure that the REA captured the breadth of existing studies, we developed a set of search terms to cover three main categories, namely: *habitat*-coral reefs, *cause of problem*-nitrogen, and *ecosystem service impacted*- such as tourism (Supplementary Table S1). This focus was due to relevant policies and research evidencing that coral reefs yield high levels of ecosystem services to millions of people (e.g., Eddy et al., 2021) but are also particularly vulnerable to nitrogen pollution (e.g., Andrello et al., 2022). The search design was informed by the literature and by project experts in the fields of marine biology/ecology, environmental economics, and ecosystem services.

For the "habitat" category, after several search iterations and expert consultations with project partners with expertise on marine ecology, we determined to use five terms for coral reef: atoll, coral, reef, Zooxanthella, and *Symbiodinium*. This study had a focus on coral reefs, however the review revealed papers with other objects of study that were relevant and thus included in the analysis, i.e., habitats, estuary, catchment, coastline, fisheries, and coastal lagoons. Note that several social science papers were excluded as they focused on the source of pollution not on the impacts of nitrogen pollution.

The "*cause of problem*" category was centered around anthropogenic nitrogen pollution (excludes natural sources e.g., bird feces) and all its forms and commonly used synonyms were included, following project partner recommendations and the literature (e.g., Compton et al., 2011). Synonyms, such as eutrophication and sewage, were included to cover for policy and social science publications that were unlikely to use technical terms like NO_3. A total of 27 terms were used under the problem category.

The Common International Classification of Ecosystem Services (CICES version 5.1; https://cices.eu/) was used to categorize the ecosystem services that were impacted by nitrogen pollution. The classification level used was "class" which had a direct link to society via benefits. This "*ecosystem service impacted*" category was the largest and included commonly used terms that are synonyms of known ecosystem services e.g., diver and snorkeling for recreation and tourism. A total of 99 terms were included in the impact category search.

Supplementary Table S1 presents the search terms for the three categories with color coding for each type of ecosystem service. Terms arranged horizontally were linked through "AND," while terms arranged vertically were linked by "OR" in the search. Note that different search operators were used to ensure a comprehensive examination of terms was achieved, e.g., "protect*" would pick up "protected" and "protection"). The search was not time constrained and aimed to be global although a focus on coral reefs meant that mainly tropical studies were found.

2.1.1 Search process

The literature search (with no back date) was carried out in June 2020 using Web of Science, which is one of the largest and most comprehensive publication databases covering both natural and social sciences, providing a powerful tool for identifying relevant literature. Search terms (Supplementary Table S1) were actioned in one go and search queries yielded 4,084 results. All search queries were imported into EndNote and five duplicates were removed at this stage. To ascertain the relevance of individual studies, all papers were subjected to two sequential screenings: (i) examination of title and abstract; and (ii) examination of full paper. The first screening was piloted three times to ensure researchers were obtaining similar selected and excluded papers based on the three categories used for the search terms. After titles and abstracts were checked for relevance, 443 papers were retained, and pdfs were obtained for these. After full papers were read, 19 were retained for data extraction. Papers excluded at the full text stage consisted of studies that were missing one of the three categories: problem, location, or impact. Both screenings were carried out by the researchers, dividing papers equally between them.

2.2 Data extraction and analysis

Once the final selection of papers was complete, papers were equally distributed between the researchers for data extraction into a pre-determined Excel spreadsheet with some multiple-choice options to facilitate comparability. Data extraction and analysis covered six categories: paper characteristics (e.g., year of publication, study scale and location, study aims), marine object of study (e.g., type of reef or species, impacts on reef), nitrogen (e.g., source activities, type of nitrogen), other pollutants or stressors (e.g., names of up to three other stressors, joint impact with nitrogen), ecosystem services and people (e.g., type of ecosystem services, methods used to assess impacts, groups of people impacted, quantification of impacts), and measures, actions, and regulations (e.g., nitrogen abatement, regulatory framework, actions recommended for mitigation).

3 Results

3.1 Study descriptions

All final papers reviewed were journal articles published between 2005 and 2020 (Figure 1). There was a spike of

TABLE 1 Summary of findings relating to object of study and pollution (N source activities are ranked by frequency of mention in papers).

Publication	Location	Main aim	Object(s) of study	N impact on object of study[a]	N pathway to object of study	N source activity[b]	N indicator[c]	WQ co-stressor[d]	Env. co-stressor[e]
Greiner et al. (2005)	Australia	Solutions, measure pollution, assess pollution impacts	Catchment	–	Several	1. Agric,2. Defor, 3. LUC	Water quality	TSS, Chem, P	–
De Valck and Rolfe (2018)	Australia	Trade-offs	Coral reef, mangrove, seagrass	Cover, Disease, Bleach, Repro, Shift, Algae, Crown, Diverse, Cover-M, Cover-S	Several	1. Agric,2. LUC, 3. LUC	N-load	TSS, Chem	Sedim
Kragt et al. (2009)	Australia	Trade-offs	Coral reef	Cover, Diverse, Diverse-F	–	–	ReduC	–	–
MacDonald et al. (2015)	Australia	Trade-offs	Coral reef, seagrass, water	Health, Cover-S	Sewage	–	Several	–	Sedim
Butler et al. (2013)	Australia	Trade-offs	Catchment	–	Flood plumes	1. Agric,2. LUC, 3. Defor	Water quality	–	–
Rolfe and Windle (2011)	Australia	Trade-offs	Coral reef, water	Diverse, Algae	Run off/erosion	1. Agric,2. Sew-R, 3. Sew-I	Water quality	P	Sedim
Schuhmann et al. (2019)	Barbados	Trade-offs	Coral reef, beach, marine resources, water	Cover, Health, WQ-R	Sewage	1. L-tour, 2. Sew	ReduC	Patho	–
Anbleyth-Evans et al. (2020)	Chile	Perceptions	Fisheries, marine resources, coral reef	Cover, Algae, Diverse-F, Cover-SF	Aquaculture	1. Aquaculture	Eutro	Chem, Metal	Overexp
Aziz et al. (2018)	Colombia	Measure pollution	Water	–	Several	1. Sew-T, 2. Agric, 3. Sew-I	Water quality	BOD, Patho, TSS	–
Baum et al. (2016)	Indonesia	Assess pollution impacts	Fisheries	Other-F	Sewage	1. Sew	–	Metal, Chem, Diesel	Overexp, Other(2)
McClenachan et al. (2018)	Japan	Trade-offs	Coral reef, fisheries, water	Health, Cover, Diverse-F, Abu-F, Size-F	–	–	–	–	Sedim
Mata-Lara et al. (2018)	Mexico	Perceptions	Coral reef, marine resources	Cover, Algae, Disease, Rugos, Structure, Diverse, Other-F	Sewage	–	–	–	Sedim
Moynihan et al. (2012)	Tanzania	Measure pollution	Coral reef, water	Algae, Urchin	Flood plumes	1. Sew,2. Agric	N-load	Patho	–
Rehr et al. (2012)	USA	Solutions	Coral reef	Health	–	1. LUC,2. Sew, 3. Agric	–	P, BOD, TSS	–
Barnes et al. (2019)	USA-Hawaii	Trade-offs	Coral reef, water	Heat-T, Structure, Shift, WQ-R	Groundwater	1. Sew-R, 2. L-tour, 3. Agric	N-load	–	Heat, CC
Levine and Saufea-Le'au (2013)	USA-American Samoa	Perceptions	Fisheries	Health, Cover, Abu-F	Run off/erosion	1. LUC	–	–	Overexp, Xtreme, Sedim, Other

(Continued)

10.3389/focsu.2024.1350159

TABLE 1 (Continued)

Publication	Location	Main aim	Object(s) of study	N impact on object of study[a]	N pathway to object of study	N source activity[b]	N indicator[c]	WQ co-stressor[d]	Env. co-stressor[e]
Ford et al. (2018)	Global	Solutions, measure pollution, assess pollution impacts	Coral reef	Cyano, Algae, Repro, Cover	Several	1. Sew-T	Sewage	DOC, P, Metal	Light, Heat, Xtreme, CC, OA
Kermagoret et al. (2019)	(Conceptual)	Trade-offs	Coral reef, sandy beach, coastal lagoon	–	–	–	Eutro	P	–
Wear (2019)	(Conceptual)	Solutions, assess pollution impacts	Coral reef	Cover, Disease, Bleach	Sewage	1. Sew	Water quality	Patho, Chem, Metal	Sedim

[a] Abu-F, abundance fish; Algae, algal bloom or increase; Cover, reduced coral reef or mangrove (-M), seagrass (-S), shellfish banks (-SF); Crown, Crown-of-thorns outbreak; Cyano, cyanobacterial mats; Disease, Coral disease; Diverse, reduced reef diversity or fish(-F); Health, reduced reef health; Heat-T, reduced coral heat stress tolerance; Other-F, reduced fish catch or poor condition of fish (as described by papers); Repro, reduced reproduction of coral reefs or seagrass(-S); Rugos, decreased reef rugosity; Shift, Coral to algal phase shifts; Size-F, reduced fish size; Structure, increased bio-erosion of reef structure; Urchin, abundant sea urchins; WQ-R, reduced water quality; [b] Agric, agriculture run-off; Defor, deforestation; L-tour, Land-based tourism; LUC, Land use change; Sew, general/unspecified sewage or run-off from industrial (-I), tourism (-T) or residential (-R) activities; [c] Eutro, eutrophication; N-load, nitrogen loading; ReduC, reduced coral cover; [d] BOD, Biochemical oxygen demand; Chem, pesticides, antibiotics, or toxins; DOC, Dissolved organic carbon; Metal, heavy metals; P, Phosphorous; Patho, Bacterial coliforms; TSS, total suspended solids; [e] CC, bleaching due to climate change; Heat, heat stress; Light, light stress; OA, ocean acidification; Overexp, fish overexploitation; Sedim, sedimentation; Xtreme, extreme weather events; WQ, water quality.

publications in 2018 and 2019, coinciding with the writing and uptake of the (a) declaration of International Decade for Action on Water for Sustainable Development, 2018-2028; (b) the adoption of the Resolution on Sustainable Nitrogen Management, during the Fourth Session of the UN Environment Assembly (UNEA-4; March 2019) and (c) the Launch of the UN Global Campaign on Sustainable Nitrogen Management in Colombo, Sri Lanka (October 2019). Two thirds of papers (69%) provided information on start and end date for data collection or modeling. The duration of data collection ranged from 2 weeks up to 16 years, although the median was 0.5 years hinting at the difficulty in undertaking long-term studies with consistent monitoring activities to address the societal impacts of nitrogen pollution.

Most papers were solely marine based (69%), while 26% of papers included land in area of study and one (5%) did not specify. We found that 84% of papers specified the location of study, while the remaining papers were either conceptual or review papers that did not include primary data. Papers most often focused on a regional scale (53%), followed by a local (31%), global (11%) and national scale (5%). Figure 2 shows the geographical distribution of papers, with a predominance of studies in Australia (mainly Great Barrier Reef) followed by the USA (in Florida, Hawaii, and American Samoa). Key coral reef regions – Central America, the Caribbean, Africa, and the Middle East – were un- or under-represented in the reviewed papers. Interestingly, only four papers specified the area covered by the study, ranging from 197 to 423,070 km^2 with a median of 349,294 km^2.

A wide range of aims were pursued in the reviewed papers, most focused on one aim (79%), few had two or three aims (10.5% each). We now explain the two main aims and three other minor aims of the papers reviewed. The most frequent aim of papers (47%, 9 papers) was to investigate the "trade-offs" i.e., benefits vs. risks/disbenefits where choices are made between a policy solution at different levels associated with different environmental changes (Table 1). Environmental changes were most frequently marginal changes in marine water quality or in degradation of reefs due to nitrogen pollution. The trade-offs due to environmental change were most often involving negative effects on tourism (e.g., diving, snorkeling) and habitat condition (e.g., beach width, coral reef health). Three quarters of trade-off papers, trade-offs under different scenarios were assessed using a non-monetary valuation approach, either contingent behavior or choice experiment, and one quarter of trade-off papers through different frameworks (see Table 2). The second most common aim (21%, four papers) was the identification and development of "solutions" for nitrogen pollution, e.g., threat abatement strategies, alternative management options, provide a framework. Other aims included the "assessment of socio-ecological impacts of nitrogen pollution on coral reefs and/or society" (11%); the measurement of nitrogen pollution" (such as extent of cyanobacterial mats, pollutant concentration or water quality, or indicators of pollution, 11%); and the study of "perceptions" and knowledge of locals, most often fishers, on marine management and pollution (10%).

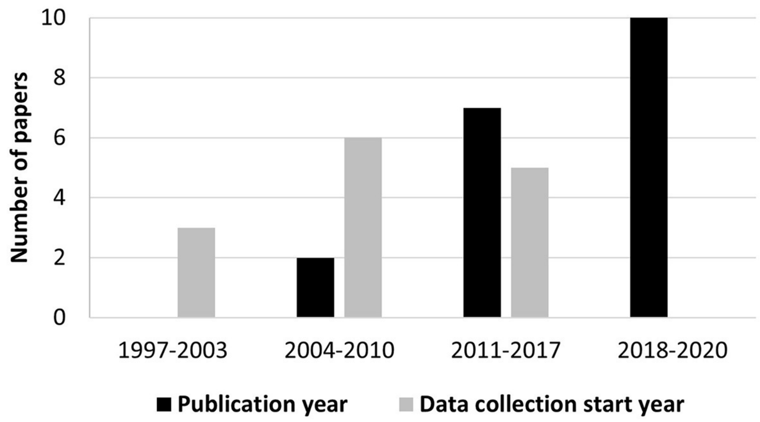

FIGURE 1
Number of papers in the Rapid Evidence Assessment by publication year and start year of data collection/modeled.

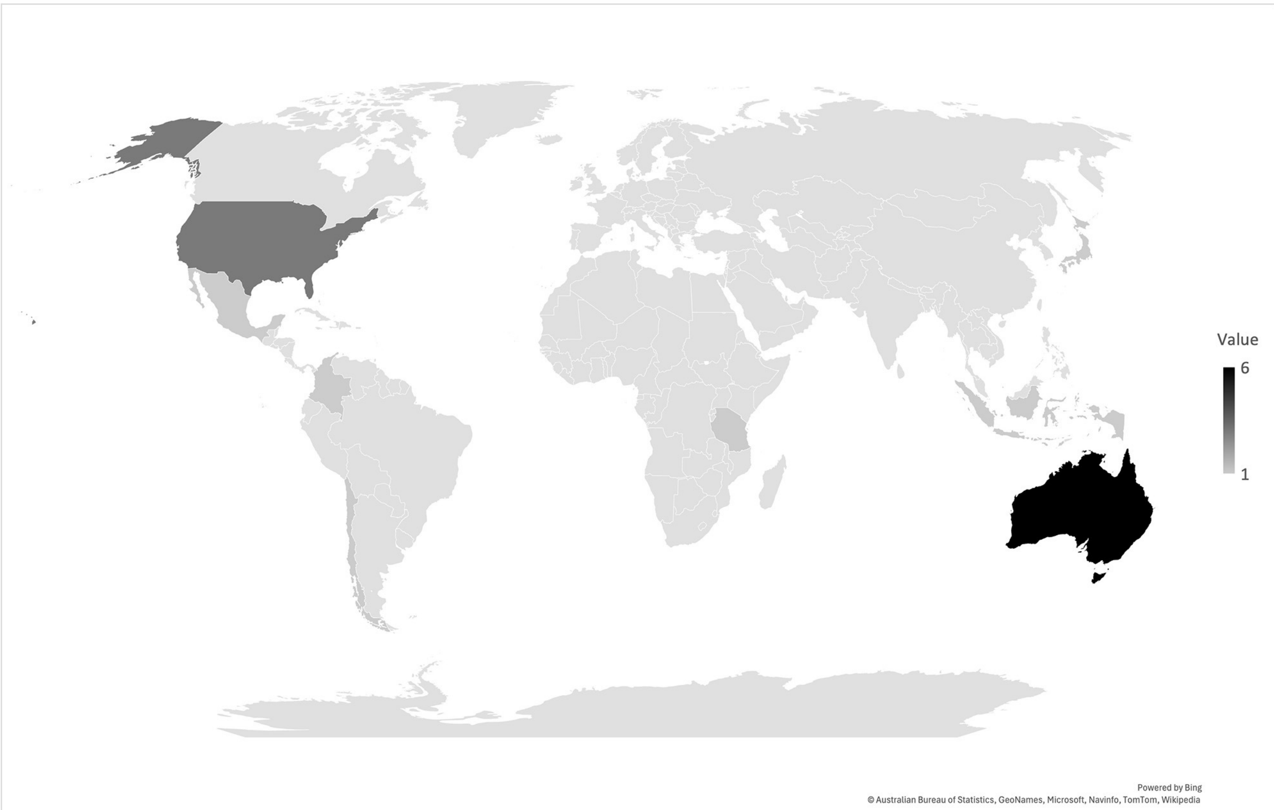

FIGURE 2
Density map of study locations of reviewed papers.

3.2 Marine object of study

Almost half of papers (47%, nine papers) studied one marine object of study, 26% (five papers) studied two objects, 21% (four papers) studied three objects, and 5% (one paper) studied four objects. The most studied marine object of study was coral reef (74%, 14 papers), followed to a lesser extent by seawater (37%), other habitats (32%), fisheries (21%), marine resources (16%), and catchment (11%). Note that the few papers not specifically studying coral reefs, are relevant to this habitat, e.g., Greiner et al., 2005 studies a catchment which includes coral reef. These objects of study reveal a prevalence of papers on both coral reef conservation and water quality assessments, regularly studied together.

Papers often referenced secondary data on the impacts of nitrogen and other threats on coral reefs. Still, 74% of papers had

TABLE 2 Summary of findings relating to impacted ecosystem services in revised papers (societal groups impacted are ranked based on the focus of each paper).

Author and publication year	Type of study	Methods to assess ES impact[a]	ES impacted[b] (number of tourist activities)	Societal groups impacted	Impact(s)[c]
Greiner et al. (2005)	Primary research	Multi-Criteria Analysis (MCA)	Fish, **Tour(2)**	1. Fishers, 2. Tourists, 3. Businesses	**Economic impact-TO and F**
Anbleyth-Evans et al. (2020)	Primary research	Interviews, participatory GIS	Fish(2)	1. Fishers, 2. Tourists	**Reduced income-F**
Kragt et al. (2009)	Primary research	Contingent valuation	**Tour(2)**	1. Tourists	**Reduced income-TO**
Levine and Sauafea-Le'au (2013)	Primary research	Interviews	Fish, Cult	1. Fishers	Reduced fisheries, lost traditions
MacDonald et al. (2015)	Primary research	Choice experiment	**Tour(2)**, Fish, Nurs, Aest	1. Residents and Tourists	Reduced coastal amenity
Mata-Lara et al. (2018)	Primary research	Survey, interviews	**Tour**, Prot	1. General population, 2. Businesses	**Reduced income-TO**
McClenachan et al. (2018)	Primary research	Choice experiment, survey	Fish, Nurs(2), Biore	1. General population	Reduced welfare-R
Moynihan et al. (2012)	Primary research	Survey, water sampling	**Tour(2)**	1. Residents and Tourists	Illness-R, **reduced income-TO**
Rehr et al. (2012)	Primary research	MCA, DPSIR, decision landscape analysis, expert elicitation	**Tour(2)**, Fish, Prot, Biore	1. Recreationists, tourists, fishers	**Economic impact-TO, RO, F**
Rolfe and Windle (2011)	Primary research	Choice experiment	Biore, Nurs	1. Residents and general population	Reduced welfare-R
Schuhmann et al. (2019)	Primary research	Contingent behavior	**Tour(3),** Biore, Aest	1. Tourists	**Reduced income-TO**
Baum et al. (2016)	Primary research	Survey	Fish	1. Residents, 2. Fishers	**Reduced income-F**, illness-U
De Valck and Rolfe (2018)	Secondary research	Value transfer, pollution impact index	Fish, **Tour(2)**	1. Fishers, 2. Businesses, 3. Residents	**Reduced economic value-TO, F, RO**
Barnes et al. (2019)	Secondary research	Cost-benefit analysis, InVEST tool	**Tour(2)**, Aest	1. Tourists,2. Residents, 3. General population	**Reduced economic value-RO**
Ford et al. (2018)	Secondary- review	Literature review	Biore, Prot, Fish	1. Residents,2. General population, 3. Fishers	Illness-U
Wear (2019)	Secondary review	Literature review	**Tour**	1. General population, 2. Tourists	Illness-U
Kermagoret et al. (2019)	Secondary- modeling	Models, literature review	Several (see text)	1. General population	Several ES decrease
Aziz et al. (2018)	Secondary- modeling	Rapid model assessment tool, water sampling	**Tour(2)**	1. Tourists, 2. Residents	Illness-T, R
Butler et al. (2013)	Secondary- modeling	Scenarios, N-SPECT tool	**Tour(2),** Fish, Cult	1. Tourists, Businesses, Fishers, Residents, General population	Several ES decrease

[a]DPSIR, Drivers, pressures, state, impact, and response model; InVEST, Integrated Valuation of Ecosystem Services and Tradeoffs; N-SPECT, Nonpoint-Source Pollution and Erosion Comparison Tool; [b]Aest, characteristics of living systems that enable aesthetic experiences; Biore, dilution of waste by marine ecosystems; Cult, characteristics of living systems in terms of culture or heritage; ES, ecosystem service; Fish, Wild animals used for nutritional purposes; Nurs, maintaining nursery populations and habitats; Prot, hydrological cycle and water flow regulation including coastal protection; Tour, tourism or characteristics of living systems promoting enjoyment through active immersions; [c]T, tourists; TO, tourism operators, mainly due to lost or reduced tourism; F, fisheries; R, residents as marine recreationists; RO, recreation operators; U, unspecified, but refers to users of marine water column.

40 mentions of observed, perceived or study site scenario impacts of nitrogen on coral reefs (see 14 unique impacts in Table 1). These mentions were quite broad, at times a mix of cause and effect and of direct and indirect impacts. The most frequently mentioned impact of nitrogen pollution on coral reefs was reduced coral cover, followed by algae increase, reduced reef health, and reduced reef diversity. For other (non-coral) marine objects of study, 58% of papers had 16 mentions of observed, perceived or scenario impacts of nitrogen (see 7 unique impacts in Table 1). Similarly, these were quite broad, only specifying the effect of nitrogen but not explaining direct causation. The most frequently mentioned impact of nitrogen pollution on other marine objects was mainly reduced cover of seagrass, mangrove, or shellfish banks, followed by negative impacts on fish.

3.3 Pollution

3.3.1 Nitrogen pathway, sources, and indicators

Although limited detail was provided in most papers, 79% (15 papers) mentioned a pathway for nitrogen reaching the marine object of study. Of these papers, 33% mentioned sewage or wastewater systems, 27% mentioned several pathways and a couple mentioned flood plumes during the wet season and land run-off or erosion. There was only one mention each of groundwater and aquaculture (Table 1). These broad pathways evidence a lack of specification on the ways that nitrogen pollution reaches the object of study. Often the "several" category just referred to the sources of nitrogen identified in the literature or in the study, these are described as follows.

The three main activities reported to generate nitrogen pollution were extracted from each paper: 74% (14 papers) mentioned a main or first source activity, 47% (nine papers) mentioned a second and 37% (seven papers) mentioned a third activity. Most papers mentioned sewage or wastewater as the activity generating marine nitrogen pollution: five general, and two due to each of the following: residential, industrial and tourism activities sewage. Agriculture was the second most mentioned source activity, followed to a lesser extent by land-use change (LUC; i.e., land clearing for livestock, urbanization, and development), land-based tourism, deforestation, and aquaculture. There is a clear lack of clarity in nitrogen pollution source activities, potentially due to insufficient or non-existent water quality monitoring and non-point pollution sources.

Regarding the pollutant, all papers referred in some way to the term "nitrogen" directly, however two-thirds of papers (68%) referred only broadly to nitrogen pollution, eutrophication, or nutrients. Only a few specific papers referred to total nitrogen (i.e., Dissolved Inorganic nitrogen + Dissolved Organic nitrogen; 16%), ammonium NH_4 (11%), and nitrate NO_3 (5%). When papers mentioned a second type of nitrogen studied, these were also at times vague (21% of papers), referred to as: pollution, nitrate, particulate form, and $\partial^{15}N$ isotopes. The lack of specificity in nitrogen type (indicative of monitoring/measuring nitrogen in water) creates difficulty in elucidating firstly, if there is a nitrogen problem and secondly, the extent of the potential problem.

Papers were reviewed for the implicit or explicit indicator used to detect nitrogen pollution at study sites. Fourteen papers (74%) mentioned an indicator, including water quality (26%), nitrogen loading (16%), reduced coral cover or eutrophication (11% each), and sewage or several (5% each). These results emphasize a potentially ambiguous approach to reporting on nitrogen pollution. Only three papers provided pre- and post-nitrogen loading levels for their studies. Two papers had information about baseline or threshold nitrogen loading levels (i.e., described as either being a "healthy reef" or as "dominant hard coral"), although several papers cited other works providing baseline datasets for the study area or region that were subsequently incorporated into models and scenarios. Six papers included information regarding actual or modeled post-nitrogen loading levels, some quite specific (e.g., tons of nitrogen per year, ammonium concentrations), but others descriptive (i.e., as a shift to either "degraded reef', "eutrophic/dominance of algal turf and macroalgae and hyper-eutrophic/dominance of cyanobacterial mats', or "algal dominance') or on a scale of pollution (i.e., very high, high, medium, low). Note that three of the specific studies refer to the same Australian Great Barrier Reef dataset.

3.3.2 Other pollutants and stressors

Almost two-thirds of papers (63%) studied at least one additional pollutant or stressor besides nitrogen. Of these, six papers looked at three other pollutants, two papers looked at two others and four papers looked at one other. The most studied pollutants or stressors alongside nitrogen were phosphorous and chemicals (5 times each), followed by total suspended solids, heavy metals, and pathogens (4 times each), Biochemical Oxygen Demand (BOD; twice each), and Dissolved Organic Carbon (DOC) and diesel (once each; Table 1). Chemicals included antibiotics, pesticides, surfactants, and toxins; heavy metals included arsenic, mercury, selenium, and/or lead; and pathogens included bacteria *E. coli*, total/fecal coliforms, and bacteria.

Similarly, over half of papers (58%) considered other environmental stressors that contributed to impacts on the marine objects of study. The most mentioned was sedimentation (7 times), followed by overfishing and "other" direct anthropogenic actions e.g., wharf building, tourism, poor enforcement (three times each), heat stress and bleaching (twice each), extreme weather events, light stress, and ocean acidification (once each, Table 1). All these pollutants, stressors and environmental variables likely interact with nitrogen and contribute to impacts in the marine environment in complex and cumulative ways that are not disentangled in the reviewed papers.

3.4 Ecosystem services and societal groups impacted

Ten papers (53%) studied one ecosystem service (ES) and nine papers (47%) mentioned several ecosystem services. The most often studied ES was "characteristics of living systems promoting enjoyment through active immersions" (CICES code: 3.1.1.1; https://cices.eu/) which includes international tourism and local recreation activities such as swimming, snorkeling, fishing, diving (Table 2). The second most studied ES was "wild animals used for nutritional purposes" (1.1.6.1) which mostly included fisheries and one mention of foraging for shellfish. Other ES studied included "dilution of waste by marine ecosystems" (5.1.1.1), "hydrological cycle and water flow regulation including coastal protection" (2.2.1.3), "characteristics of living systems that enable aesthetic experiences" (3.1.2.4), "characteristics of living systems in terms of culture or heritage" (3.1.2.3), and "maintaining nursery populations and habitats" (2.2.2.3). Note that it was not possible to distinguish in papers if water quality impacts were referring to bioremediation (decomposing) or filtration of waste or other. So, these ES were all classified as "dilution of waste by marine ecosystems" (5.1.1.1). Further, papers sometimes referred to biodiversity or to nursery habitat, both classified under "maintaining nursery populations and habitats'. Many of the papers did not use a specific framework linking impacts to society (such as the ecosystem services framework). Due to this lack of specificity and link to society, only those ES directly attributed in the papers were included in our analysis.

3.4.1 Approaches to assess impacts of nitrogen pollution on society

Two thirds of papers were based on empirical research generating primary data (63%), followed by reviews or research with secondary data (21%) and modeling (16%). The 12 primary research papers that employed methods such as surveys, interviews, valuations, or multi-criteria analysis (12), focused on asking peoples' perceptions, views, or values for the impacts of nitrogen pollution. These studies had specific objectives and resources that limited the number and type of participants. Sample sizes varied widely, from <10 people to surveys covering 2,550 people. However, there was a clear distinction across methods, with multicriteria analysis studies having small samples, surveys generally having small to mid-size samples and valuation approaches having the largest sample sizes.

The seven papers that provided quantifiable or monetary estimates of the impact of nitrogen pollution employed either primary data valuation approaches (contingent valuation or behavior, choice experiments-with hypothetical scenarios), value transfer-based on literature values, or cost-benefit analysis for sewage treatment (indirect value of impacts). A closer look at the scenario attributes of the five valuation papers revealed the use of impacted objects of study, from reduced coral cover or health to murky water, that may, or may not include impacts by other pollutants or stressors. Only Rolfe and Windle (2011) included an attribute with a specific reduction in nitrogen i.e., one water quality improvement unit equals an annual reduction of 100,000 t of soil plus nutrients: 200 t nitrogen þ 46 t phosphorus. However, this paper was still valuing the reduction in nitrogen and sedimentation together and its joint impacts on reefs i.e., percentage reef cover in good health.

3.4.2 Societal impacts from nitrogen pollution

Papers reviewed reported impacts of marine nitrogen pollution on one to six societal groups, but almost half of papers (47%) focused on tourists and fishers (Table 2). Overall, the most frequent focus of papers was on tourists, residents, general population, and fishers. These findings highlight the limited research on impacts of marine nitrogen pollution on other groups, such as businesses.

The most frequently mentioned category of impact on ecosystem services for society was "reduced income" or economic impact on tourism or recreation operators, or fisheries in 10 papers (53%), followed by human illness and less tourists (or tourism opportunities) in four papers each (21%) (Table 2). Other less studied impacts included decreased ES, reduced welfare, reduced fisheries, and loss of cultural traditions. However, two thirds of all papers (63%) only reported that there was an impact, without quantifying it. Only seven papers attempted to quantify, either directly or indirectly, the impacts of marine nitrogen pollution on society. Two papers quantified the impacts of nitrogen specifically (i.e., nitrate and dissolved inorganic nitrogen) using modeled scenarios. Barnes et al. (2019) found that, applying the InVEST model, weighted Photo User Days (a proxy for visitation and recreational value, with higher values representing higher visitation) ranged from 22 in a low sewage treatment scenario (6.12 kg day^{-1} nitrate flux) up to 137 in a maximum sewage treatment scenario (4.83 kg day^{-1} nitrate flux). De Valck and Rolfe (2018) estimated the marginal changes in total economic value for three industries (i.e., tourism, recreation, commercial fishing) from a 1% increase in dissolved inorganic nitrogen (DIN) loads. The impact of DIN loads was higher than the impact of sediments or pesticides. The latter study proves to be the most comprehensive and direct approach to estimating impacts of nitrogen pollution on society.

A method that stands out for eliciting peoples' preferences or values for coral reefs and other aspects that affect ecosystem services to society are non-market valuations, either contingent valuation method (CVM, two papers) or discrete choice experiments (DCE, three papers). CVM is characterized by deriving a value for one defined scenario. Kragt et al. (2009) used CVM to estimate the value per recreational reef trip for an average diver or snorkeler. Schuhmann et al. (2019) looked at the intention to return by tourists if there was a decline in water quality, and just a 5% decline in quality resulted in over 70% of respondents changing their intention to return. However, DCEs obtain values for several scenarios including a set of attributes with different levels. Rolfe and Windle (2011) and MacDonald et al. (2015) studied the values for water quality (i.e., amount of nutrients or days of water clarity/murkiness) plus either seagrass increase or improvement in reef health. Finally, McClenachan et al. (2018) valued the support for increasing the creation of marine protected areas via the increase in fish catch, coral cover, and biodiversity, and the decrease in coastal development. Even though these papers show a clear and often high value for reducing nitrogen pollution impacts, CVM does not allow to disentangle values for different attributes and both methods often jointly account for reducing the impacts of several overlapping threats or pollutants e.g., improve water quality or reduce pollution. Further, both CVM and DCE obtain values for hypothetical or planned environmental changes, not actual changes.

3.4.3 Society's understanding on how they are impacted

A third of papers (32%) involved research asking peoples' knowledge or opinions relating to the impacts of marine nitrogen pollution. Interestingly, opinions were almost equally divided between negative and others (i.e., contradictory or benign). Of the three papers reporting negative impacts, Levine and Sauafea-Le'au (2013) found that over 60% of fishermen interviewed reported that populations of reef fish had declined in abundance due to extensive population growth and development, modern fishing methods and changes in coral reef ecosystems. Some fishermen also reported the erosion of cultural fishing traditions. Anbleyth-Evans et al. (2020) found that fishers reported declines in natural fish or shellfish stocks due to aquaculture pollution, whilst Baum et al. (2016) reported that 24% of fishermen reported (unspecified) water pollution to be the cause of marine resource decline and 68% of them mentioned it as the main cause for human illness at the study site.

It is of particular interest that three papers found contradictory or benign views of the impacts of marine nitrogen pollution. McClenachan et al. (2018) found that respondents perceived increases in water pollution and sedimentation in coral reef areas with associated impacts. However, most respondents reported that algal growth in coral reef areas remained stable or decreased, which would most likely indicate a healthy, rather than a degraded reef ecosystem. Moynihan et al. (2012) found that interviewees were aware that untreated sewage entered the ocean and of the associated health hazards, but all except one swam frequently and had little concern about health effects. The local attitude toward pollution was one in which humans cannot have a significant impact on their environment as "*the ocean cannot be polluted.*" Mata-Lara et al. (2018) found that on average 84% of the population of the touristic town of Akumal, Mexico had an inaccurate perception of the condition and threats to marine resources i.e., coral reef and beach. Researchers ascribed this lack of awareness to residents" limited interaction with the marine environment despite being coastal. Tourism service providers were also interviewed, and they evidenced a much higher awareness of how the condition of marine resources had worsened in recent years i.e., based on water quality and reef condition.

3.5 Abatement measures and policy for marine nitrogen pollution

3.5.1 Nitrogen abatement and responsible parties

Abatement refers to avoiding nitrogen pollution from reaching the marine environment and mitigation refers to dealing with the impacts when nitrogen pollution reaches the marine environment. A total of nine papers (47%) mentioned abatement measures, either at or close to source or downstream from source, and either implemented or as recommendations. The most frequently mentioned actions were around wastewater treatment and direct enforcement of pollution controls. Five papers mentioned establishing, financing (i.e., funding or homeowners" fee), or improving wastewater treatment/management, including toilet systems, stormwater diversion and artificial wetlands. Similarly, five papers directly recommended stronger controls or prohibitions on releasing untreated wastewater, creation of new laws, and enforcement of existing laws on industry. Only two papers referred to halting or changing land use practices to reduce fertilizer use. Regarding downstream abatement, one paper mentioned abatement measures which included changing aquaculture practices (not specifying how), and another mentioned the reduction of urban pollution by wastewater treatment downstream before it enters the sea.

Four papers suggested assigning protection status or zoning, either through a marine protected area, integrated coastal zone management or buffer areas. Four papers mentioned innovative actions, such as cross-sectorial or corporate partnerships, technological innovations (though unspecified), education and capacity building on attitudes and preferences in land use practices and integrating fishers" local ecological knowledge. Two papers recommended improved farm practices and land use changes to reduce pollution, including limits to fertilizer use. Other indirect measures mentioned included: starting water quality monitoring, replanting seagrass, restoring reefs, and implementing a fisheries management area to reduce the interactive effects of nitrogen pollution and overfishing on coral reef health, and the potential for water quality trading of water pollution rights. This wide range of actions represents the local context and pollution issues at each study locality, but it is promising to see that the most often mentioned actions deal directly with causes of marine nitrogen pollution.

A total of eight papers (42%) mentioned parties responsible for nitrogen abatement at their study sites. The state (i.e., in USA and Australia) or national authorities (7) are most often considered responsible for abating nitrogen pollution. When specified how, it was by "*using public funds to pay landholders to reduce emissions in agricultural runoff to improve water quality entering the Great Barrier Reef*" or by highlighting inaction "*stakeholder momentum has been dampened by a lack of match funding by municipal and state government to build a water treatment plant and sewage network.*" In one paper, private companies and local governmental institutions were jointly mentioned, and one paper mentioned the state government and homeowners.

3.5.2 Policy and management of marine nitrogen pollution

Over half of papers (58%) mentioned policy or management tools for marine nitrogen pollution. Out of these, five papers referred to at least one national or international policy. For instance, Aziz et al. (2018) referred to the Caribbean Environment Programme, the Protocol Concerning Pollution from Land-based sources and activities and a UNEP regional Sea Program whose main legal instrument is the Cartagena Convention. Schuhmann et al. (2019) mentioned the Barbados Government's new strategic direction to develop a strong blue economy, with the intention to follow a "Roof to reefs" model, requiring management of land-based activities. Rehr et al. (2012) mentioned several national and Florida state laws such as the National Pollution Discharge Elimination System, FL Sec 62-043 Surface Water Improvement and Management Act, PL 101-605 Florida Keys National Marine Sanctuary and Protection Act, and the 16 USC 6401 Coral Reef Conservation Act. Greiner et al. (2005) and De Valck and Rolfe (2018) referred to the Australian Reef Water Quality Protection Plan with water quality targets and a 2050 sustainability plan.

Further, three papers mentioned policies that prohibited or banned actions. Rehr et al. (2012; USA) mentioned the Governor's Executive Order 96-108 for the elimination of cesspits (USA) and Barnes et al. (2019; Tanzania) stated that by 2050 the state has promised to ban and remove 80,000 cesspools. Moynihan et al. (2012; USA) mentioned the Municipal Council advising against swimming in nearshore waters due to pollution, but little effort had been made to increase awareness on this issue. Including Rehr et al. (2012), four papers mentioned Marine Protected Area (MPA) existence or management tools for dealing with nitrogen pollution. De Valck and Rolfe (2018) mentioned the regulatory role of both the national government and the Queensland government to coordinate activities for water quality regulation in the Great Barrier Reef, and Mata-Lara et al. (2018) mentioned peoples' perceptions supporting a Fishing Refuge Zone and implementation of MPAs in Akumal, Mexico. However, both papers mentioned that these initiatives were not successful, either due to a mismatch between stakeholders (former paper) or to MPAs existing only on paper and not producing results (latter paper). With a more local approach, Levine and Sauafea-Le'au (2013) mentioned a territory's Community-Based Fisheries Management Program discussed by fishermen; and Anbleyth-Evans et al. (2020) mentioned regulations for private companies to test for temperature, pH, dissolved oxygen levels but not for nutrients. These findings highlight the variety and scale breadth of policies, legislation and guidelines that can and need to be implemented and enforced to reduce marine nitrogen pollution, both at the sources and sinks of nitrogen.

4 Discussion: evidence gaps and recommendations

The Rapid Evidence Assessment process revealed a small number of papers that fulfilled our search criteria on how the impact of marine nitrogen pollution affects society. Often papers mentioned uncertainty or ambiguity in marine nitrogen pollution impacts, which made it hard to link to ecosystem service impacts and thus to society. There is an ongoing paradigm shift that identifies the importance of water pollution as a top pressure on coral reefs (Andrello et al., 2022). However, this section highlights gaps in the literature and makes recommendations to allow us to better understand how and to what extent coastal societies are being impacted by marine nitrogen pollution from a range of sources, with varying impacts. The following section summarizes the recommendations into a strategic future research agenda.

There are varying strengths and weaknesses in our knowledge of the impacts of nitrogen pollution on the environment, ecosystem services and society. To improve our understanding of the impacts of marine nitrogen pollution, improvements in future research into the impacts of nitrogen pollution on the marine environment are required. First, more detailed information is required on, for instance start- and end-dates of data collection and specifying study site size and boundaries of areas sampled as best practice for replicability. More specifically, vague reporting of nitrogen type and quantified levels of pollution create difficulty in determining if there is a nitrogen problem and the extent of this problem, as different types of nitrogen act differently in the marine environment and have variable effects (Burkepile et al., 2020).

Whilst the indicators are suggestive of nitrogen pollution, nitrogen may not be the sole factor contributing to a change in these indicators. Using biological indicators such as eutrophication or reduced coral cover and even water quality are simple and cost-effective ways of identifying nitrogen pollution, but do not allow one to understand if the environmental stressor is solely nitrogen or a combination of other stressors (Wear and Vega-Thurber, 2015). Moreover, it does not identify what and how much nitrogen is physically entering the sea. Therefore, it is important to go beyond noting that eutrophication or pollution is present, nitrogen forms of pollution need to be specified and the impact of other pollutants or stressors e.g., Phosphorous, climate change, need to be clearly distinguished.

A lack of data on pre- and post-loading nitrogen levels makes it difficult to determine, both temporally and spatially, the point at which excess nitrogen loading becomes an issue for the marine environment. This makes it harder to attribute cause and effect, calculate change over time and identify potential tipping points (Ezzat et al., 2015; Burkepile et al., 2020). This is likely due to monitoring and calculating nitrogen loading often being costly in both time and money (Wear and Vega-Thurber, 2015). These findings suggest firstly that there has been a lack of long-term, historical monitoring data for many studies, and secondly that there is a genuine need for improved quantification of nitrogen concentrations when aiming to attribute impact.

Although most papers provided some information on the source and pathway of marine nitrogen pollution, this was vague. This can be problematic because the number of potential sources is large and pathways to the marine environment can be complex. This lack of clarity is potentially due to insufficient or non-existent water quality monitoring and non-point pollution sources (Malik and Szwilski, 2016). Further research is needed to understand the impacts of land use change, deforestation, land and sea-based tourism and aquaculture; especially as the latter has increased globally in the last 20 years (Naylor et al., 2021). Our findings are in line with information on the World Atlas of Coral Reefs, where although 92% of reefs have documented coastal sewage pollution problems (Wear and Vega-Thurber, 2015) the type of sewage is often either unknown or unspecified (Carlson et al., 2019; Wear et al., 2021).

There are huge geographical gaps in the research reviewed, including key coral reef regions including Central America, the Caribbean, Middle East, and Africa. This was further evidenced by only 10 out of the 29 Allen Atlas coral reef regions being covered in the review (https://allencoralatlas.org/methods/, accessed 22nd July 2022). These unstudied areas are also some of the regions with the highest nitrogen pressure on coral reefs, which include Southeast Asia, Western Indian Ocean, North Pacific Ocean, Eastern Tropical Pacific, Caribbean-Atlantic, and Middle East and North Africa (Andrello et al., 2022).

The most often studied ecosystem services impacted by marine nitrogen pollution were "characteristics of living systems promoting enjoyment through active immersions" (e.g., recreation) and "wild animals used for nutritional purposes" (e.g., fish). More research is needed to understand the impacts on other ecosystem service categories, especially as there is conceptual recognition of a much broader set impacted i.e., pathogen and nutrient regulation, climate regulation, materials, culture, trophic networks, recruitment (e.g., Kermagoret et al., 2019). The findings evidence the nascent nature of research into the ecosystem service impacts of marine nitrogen pollution.

Studies quantifying the impacts of nitrogen pollution often valued impacts e.g., reduced coral cover or murky water, that may or may not include impacts by other pollutants or stressors. Only one paper (Rolfe and Windle, 2011) included an attribute with a specific reduction in nitrogen. However, this paper was still valuing the reduction in nitrogen and sedimentation together and their joint impact on reefs. Findings evidence the need for the quantification of direct reductions in ecosystem services due to marine nitrogen pollution explicitly and cumulatively with other pollutants or stressors. Actual estimations of impacts directly linked to nitrogen would serve to provide quantification of the impacts of marine nitrogen pollution but would also verify human knowledge and perception studies for accuracy.

The most frequently impacted groups of society were tourists, residents, general society, and fishers. However, as more research is undertaken into the ES impacted, the diversity of groups affected has a potential to increase. Additionally, there is a need for further clarity on if the impacts on these different societal groups were mainly from nitrogen pollution or due to other pollutants or stressors, either individually or jointly. The most frequently reported impacts on society were reduced income, human illness, and reduced tourists. However, these impacts on ecosystem services and society were most often not quantified.

Studies assessing peoples' knowledge and perceptions of nitrogen pollution and its impacts were one of the most frequent study types in this review. The studies were almost equally divided between negative and contradictory or benign views of nitrogen pollution impacts. The latter studies reflect persistent causes reported elsewhere, including reduced awareness of existing pollution due to a lack of exposure or distorted beliefs (e.g., Gelcich et al., 2014; Mumbi and Watanabe, 2020), misinformation or low risk perception from the impacts of pollution (e.g., Quilliam et al., 2019; Ross et al., 2020), and challenges of disentangling the causes and impacts of different threats on the marine environment (e.g., Lotze et al., 2018).

There do not seem to be any clear trends in marine nitrogen pollution abatement measures, as they range from upstream (e.g., land use change) to downstream measures (e.g., wastewater treatment). This wide range of measures reflect local contexts and specific pollution issues. Parties responsible for nitrogen seem to be much less discussed and are mainly local or national authorities. There is a variety and scale breadth of policies, legislation and guidelines to manage marine nitrogen pollution, but it was clear that enforcement and a mix of government and other parties will most often lead to more sustainable and comprehensive abatement measures (e.g., Abdulla and Naser, 2021; Wear et al., 2021).

Based on the previous section we can summarize our recommendations into three target areas covering nine priority research questions on marine nitrogen pollution at the nature-society interface:

1. Scope and standardization of nitrogen pollution research

   1.1 Can there be agreement on best practice guidelines for monitoring, measuring, and reporting nitrogen pollution around the world?
   1.2 What are the individual and cumulative quantified impacts of nitrogen with other pollutants and stressors on the marine environment?
   1.3 What are the impacts of pollution in different geographical areas with high nitrogen pressure on coral reefs and marine environments?

2. Quantify marine ecosystem service impacts of nitrogen pollution

   2.1 How can we ensure more comprehensive research into the impacts of nitrogen pollution on all marine ecosystem services to society?
   2.2 How can interdisciplinary research be promoted and mainstreamed to ensure understanding and quantification of the impacts of nitrogen pollution from the marine environment, through ecosystem services, to society?
   2.3 To what degree are the marine ecosystem service impacts based on changes of levels of nitrogen pollution alone and cumulatively with other pollutants and stressors?

3. Marine nitrogen pollution at the science-policy-society interface

   3.1 How can scientists work better in partnership with the private sector and decision-makers to measure and monitor the impacts of marine nitrogen pollution?
   3.2 How can marine nitrogen pollution research lead to concrete policy recommendations that ensure win-win solutions across societal groups?
   3.3 How can researchers contribute to creating awareness of marine nitrogen pollution and its impacts?

Author contributions

OR: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. JA: Data curation, Formal Analysis, Funding acquisition, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. NB: Funding acquisition, Resources, Supervision, Writing – review & editing. MW: Data curation, Formal analysis, Funding acquisition, Resources, Validation, Writing – review & editing. SP: Funding acquisition, Writing – review & editing. FS: Conceptualization, Funding acquisition, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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