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Why are there so many definitions of eutrophication?

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Abstract

Because of the first observations in the 1900s of the oligotrophic and eutrophic states of lakes, researchers have been interested in the process that makes lakes become turbid because of high phytoplankton biomass. Definitions of eutrophication have multiplied and diversified since the mid-20th century, more than for any other ecological process. Reasons for the high number of definitions might be that the former ones did not sufficiently describe their causes and/or consequences. Global change is bringing eutrophication more into the spotlight than ever, highlighting the need to find consensus on a common definition, or at least to explain and clarify why there are different meanings of the term eutrophication. To find common patterns, we analyzed 138 definitions that were classified by a multiple correspondence factor analysis (MCA) into three groups. The first group contains the most generic scientific

Alexandrine Pannard and Philippe Souchu contributed equally to the work.

definitions but many of these limit the causes to increased nutrient availability. A single definition takes into account all causes but would require additional work to clarify the process itself. Nutrient pollution, which is by far the primary cause of eutrophication in the Anthropocene, has generated a second group of environmental definitions that often specify the primary producers involved. Those definitions often mention the iconic consequences of nutrient pollution, such as increased algal biomass, anoxia/hypoxia and reduced biodiversity. The third group contains operational definitions, focusing on the consequences of nutrient pollution, for ecosystem services and therefore associated with ecosystem management issues. This group contains definitions related to regulations, mainly US laws and European directives. These numerous definitions, directly derived from the problem of nutrient pollution, have enlarged the landscape of definitions, and reflect the need to warn, legislate and implement a solution to remedy it. Satisfying this demand should not be confused with scientific research on eutrophication and must be based on communicating knowledge to as many people as possible using the simplest possible vocabulary. We propose that operational definitions (groups 2 and 3) should name the process "nutrient pollution," making it possible to refine (scientific) definitions of eutrophication and to expand on other challenges such as climate warming, overfishing, and other nonnutrient-related chemical pollutions.

KEYWORDS
definition, eutrophication, multiple correspondence analysis, nutrient pollution, process, semantic landscape

INTRODUCTION

Environmental scientists need to develop a common set of clear concepts and definitions to describe ecosystem functioning and to help societies move toward sustainability (Aronson, 2011). The concept of eutrophication is old, going back to the first observations of Naumann (1919) and Weber (1907), which described oligotrophic and eutrophic states in lakes. It remains relevant (Le Moal et al., 2019) as the process it describes is related to the greatest and the widest-reaching threat to aquatic ecosystems. Numerous definitions of eutrophication can be found in the literature, from a few words (Claussen et al., 2009) to a full paragraph (Díaz et al., 2010). As early as 1980, Parma inventoried different Dutch definitions of eutrophication and found diversity in their content but also a certain confusion in the communication of the concept.

In the present study, we sought to understand why there are so many definitions, how they differ, whether they include different concepts and whether some are more consensual. We also wondered how a definition of eutrophication could address both a complex scientific subject and an environmental threat, or even management aspects. The many definitions of eutrophication found in the literature address the phenomenon through different biogeochemical (element cycle), biological (primary production) and ecological (ecosystem evolution) approaches that we deal with first. We deconstructed the process to clarify the meaning of the word eutrophication and identify the fundamentals that a definition should contain. We subsequently reviewed the elements that should be considered in a generic definition. For this purpose, we relied on a conceptual model of eutrophication, which was used for the OSPAR convention (OS for Oslo and PAR for Paris, referring to the original Oslo and Paris Conventions signed in 1992) and the European Water Framework Directive (Claussen et al., 2009, their fig. 1). We then collected definitions from scientific literature and internet sites to analyze their content in words and perception. The definitions were analyzed from various aspects (type of ecosystem, age, frequency of some words, etc.). We used multiple correspondence analysis (MCA) to obtain a graphical representation of the landscape of definitions, making it possible to describe its structure, and associations among definitions as well as the variability in cited perceptions. By this approach and highlighting some examples, we attempted to understand the reasons behind the many definitions and why the concept of eutrophication is still prone to confusion.

The context of eutrophication definitions

Eutrophication and its definitions have already been described for aquatic ecosystems (Hutchinson, 1973; Parma, 1980; Rast & Thornton, 1996) with processes differentiated into three categories: causes, direct and indirect effects (de Jonge et al., 2002). The figure of Claussen et al. (2009) based on these three categories is one of the most relevant to date (Figure 1). The flowchart highlights that, among the causes of eutrophication, increased availability of nutrients is the main process affecting primary producers. Nitrogen (N) and phosphorus (P) are the two key macronutrients that control primary production in both terrestrial and aquatic ecosystems (Elser et al., 2007). N and P occur in different forms that are not all bioavailable, that is, directly absorbable by primary producers. Depending on its origin (e.g., seafood processing or paper production, pulp), the organic matter brought to ecosystems can be a more or less important source of nutrients after remineralization. Readily bioavailable N is the inorganic forms (nitrate, nitrite and ammonium corresponding to dissolved inorganic nitrogen: DIN) and organic forms such as urea and certain amino acids (Bronk et al., 2007; Jones et al., 2005; Witte, 2011). Despite the fact that the largest N reservoir is atmosphere dinitrogen (N_2), this gas form is only bioavailable for photosynthetic organisms benefiting from biological nitrogen fixation (BNF), in particular certain cyanobacteria. Bioavailable P essentially occurs in the dissolved orthophosphate form (dissolved inorganic phosphorus: DIP) in soil solutions or in water bodies. Certain organic P compounds become bioavailable after hydrolysis by phosphatase enzymes (Nausch & Nausch, 2006; Tarafdar & Claassen, 1988). Overall, the stoichiometry of dissolved inorganic nitrogen, phosphorus

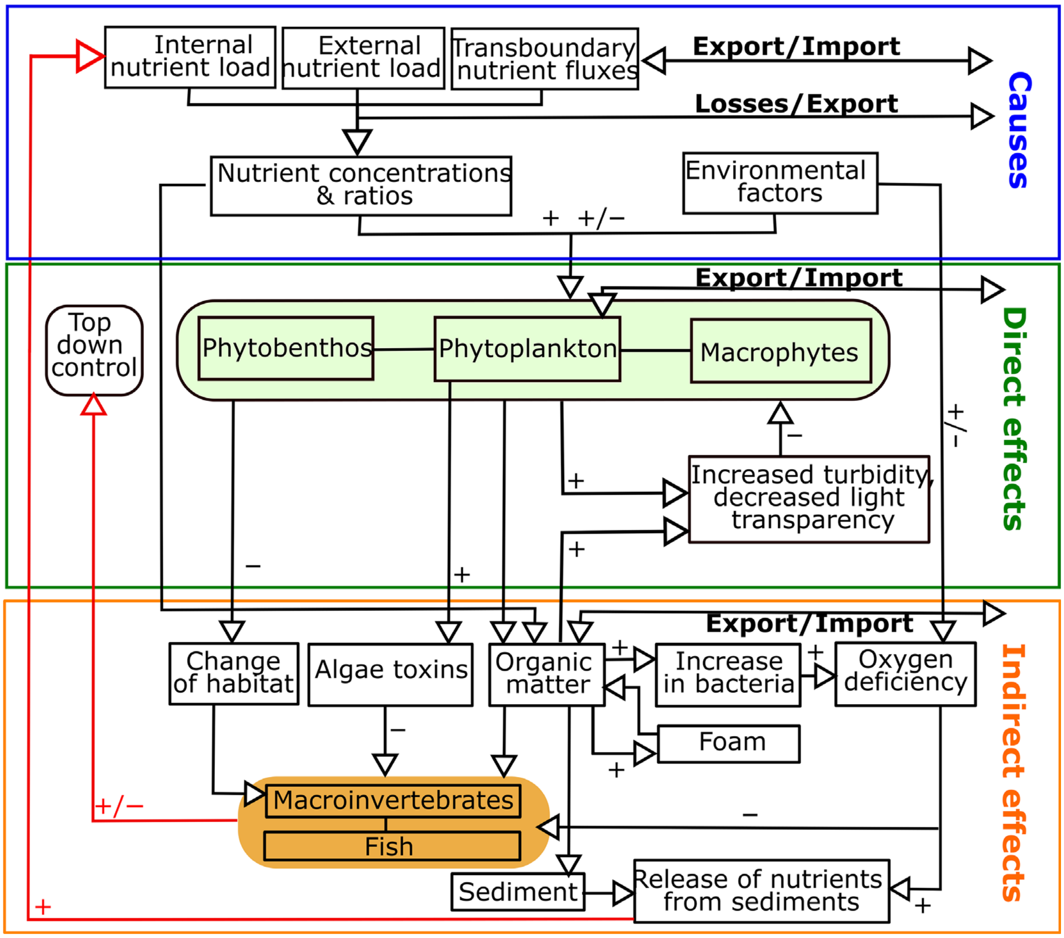

FIGURE 1 Conceptual diagram of eutrophication as proposed by Claussen et al. (2009) for all types of surface water bodies, presented as a framework for the implementation of the European Water Framework Directive. The conceptual diagram compartmentalizes the variables and processes that can help define eutrophication into three categories: causes (nutrient enrichment), direct effects with the response of primary producers and indirect effects with the response of the other biological compartments and the interaction with sediment. Variables are interconnected by positive or negative links (black continuous arrows). The toxicity produced by some algae was considered to be an indirect effect here, while it was the subject of a fourth category in Claussen. The positive feedback that consolidates the eutrophication process is shown: first the top-down control and then the internal nutrient load. The four export/import arrows refer to exchanges with the surrounding environment.

and silica (DSi) as macronutrients, and the availability of micronutrients such as iron and manganese, play an important role in the composition of primary producers that emerge as a result of enrichment with N and P (Turner et al., 1998; Zhang et al., 2019).

In the absence of human activity, aquatic ecosystems receive input of allochthonous nutrients from continents by water and air. Throughout its history, Earth has experienced changes in temperature and atmospheric gas composition accompanied by shifts in terrestrial communities (Slater et al., 2019), leading to changes in the nutrient transfer from continents to aquatic ecosystems as well as periodic intensification of upwelling in oceans (Jenkyns, 2010). Events in the catchment basin, such as fires (Spencer & Hauer, 1991), volcano eruptions (Urrutia et al., 2007) and heavy rainfall (Sadro & Melack, 2012), also provide nutrients to aquatic ecosystems. Bird droppings (Dessborn et al., 2016), and even pollen (Rösel et al., 2012), can directly bring natural nutrients to aquatic ecosystems.

When humans started clearing and burning forests, they modified the initial nutrient flow and enriched lakes and coastal waters with nutrients of natural origin (McWethy et al., 2010). Nowadays, climate change often amplifies natural mechanisms and thereby increases the nutrient flow. For instance, permafrost thawing in Arctic regions due to global warming contributes to nutrient transfer from pristine soils to aquatic ecosystems (Vonk et al., 2015), and intensification of upwelling processes in the oceans is also linked to the acceleration of climate change (Wang et al., 2015). A threshold was passed with the development of fertilizer industries, beginning with the discovery of the Haber–Bosch process in 1909 to produce synthetic nitrates and with the extraction and production of always more concentrated superphosphates (Weeks & Hettiarachchi, 2019). Humans began to alter the natural biogeochemical cycles of N and P by increasing the nutrient inputs to soils, aquatic ecosystems and the atmosphere over extremely short periods on a geological time scale (Childers et al., 2011; Galloway et al., 2008). As a result, nutrient pollution today threatens all ecosystems along the land–sea continuum (Bobbink et al., 1998; Morelli et al., 2018).

The use of bioavailable nutrients by primary producers depends on light energy, which fluctuates according to climate and the physical, chemical and morphological parameters in the aquatic ecosystems (e.g., water level, river types, residence time, stratification, turbidity, riparian vegetation, and self-shading). Variations in environmental factors can also affect the accessibility of the different nutrient stocks in the ecosystems (Smolders et al., 2006). In highly stratified marine ecosystems such as the Gulf of Mexico (Baustian & Rabalais, 2009), nutrients produced in bottom waters have a better chance of fertilizing surface waters under the effect of storms and upwellings. Increasing periods of stratification associated with climate change can also lead to lower oxygen and internal loading (Woolway et al., 2022). Drought, sea level rise, and marine storms increase the risk of salt intrusion of freshwater wetlands, leading to nutrient release from sediments to the water column (Herbert et al., 2015). Environmental factors and their variations, whether of natural or anthropogenic origin (e.g., epizootics, storms, droughts and chemical contamination), can also lead to mortality of species and consequently release of nutrients in the water due to internal recycling. Yet, external input is often the major cause of nutrient increases in aquatic systems that lead to eutrophication, often in the form of algal or sometimes excessive macrophyte growth.

Increased nutrient availability is not the only cause of eutrophication. Invasive species can induce changes at lower trophic levels and generate eutrophication (Gallardo et al., 2016). Similarly, shellfish farming modifies the plankton composition of its environment (Souchu et al., 2001). Overfishing also induces changes in the food web, generating cascading effects on phytoplankton and macroalgae (Caddy, 2000; Zaneveld et al., 2016). These positive effects on ephemeral primary producer biomass (top-down control) may be considered in the same way as nutrient enrichment (Östman et al., 2016).

Several causes of eutrophication can be added, potentially leading to synergistic effects. For example, the rise of certain species of *Sargassum* in the Sargasso Sea called golden tides might have originated from the joint increase in nutrient inputs from the Amazon River and oceanic deepwater, the latter due to the intensification of coastal upwelling (Wang et al., 2019). Zaneveld et al. (2016) have also demonstrated the synergistic effects of overfishing and nutrient pollution on coral reef degradation. Climate warming may also amplify the effect of nutrient pollution in a synergistic way, in part due to alterations in the trophic structure and food webs (Jeppesen et al., 2014; Meerhoff et al., 2022).

The direct effect of eutrophication is materialized by a higher contribution to the primary production of faster-growing species, which can lead to the elimination of slow-growing species (seagrass, kelp beds, coral reefs, macrophytes, etc.) being replaced by these more productive species (higher production-to-biomass ratios P/B), for example, opportunistic green macroalgae and phytoplankton. The transparency and color of lake water related to the presence of phytoplankton sparked the first research on the notion of eutrophication status by Hutchinson (1973), who determined that the oligotrophic state was characterized by transparent waters with low phytoplankton biomass, implying low nutrient availability. In the eutrophic state, there was higher nutrient availability and the visible presence of phytoplankton in the water. Half a century later, this concept of eutrophication still stands, yet other types of primary producers can also pose problems, such as macroalgae (Gladyshev & Gubelit, 2019) or macrophytes (often herbaceous higher plants) (Valéry et al., 2017). The mechanisms accounting for an eutrophication-induced expansion of one or the other of these primary producer groups are complex. Well known are eutrophication-induced shifts from submerged macrophytes toward phytoplankton (Scheffer, 2001; Scheffer & Jeppesen, 2007). Instead of phytoplankton, a degraded state can also consist in the dominance of floating-leaved plants, rooted or free-floating (Scheffer & van Nes, 2007; Szabó et al., 2022).

A main indirect effect of eutrophication is a simplification of the structure and functions of primary producers accompanied by a decline in species diversity. The quantitative changes in primary producers relate to the increase in the quickly recyclable biomass (e.g., phytoplankton and macroalgal blooms) following microbial decomposition that may cause hypoxia in bottom water and sediments (Díaz & Rosenberg, 2008). Anoxic crises accelerate the decline of biodiversity by eradicating the many species that cannot survive without dissolved oxygen. In aquatic ecosystems with salty waters, such as salt lakes, estuaries, and lagoons, oxygen depletion is usually followed by sulfate reduction, leading to the production of hydrogen sulfide (H_2S) (Jørgensen, 1988). This compound is toxic to a large number of organisms and amplifies damage to the biodiversity of salty aquatic ecosystems.

Internal eutrophication due to remobilization of sediment-bound phosphorus is a serious threat to aquatic systems. The phosphorus-iron–sulfur biogeochemical coupling differs between marine and brackish coastal areas and freshwater lakes (Blomqvist et al., 2004). Iron complexes with phosphate are considered to play a major role in the release or binding of phosphorus to sediments under anoxic or oxic conditions, respectively. Yet, the phosphorus binding capacity of lake sediments can be influenced by other minerals, and a paradigm shift has been proposed "Sedimentary P exchange ought to be considered as a complex process which is mainly determined by the amount and species of settled P as well as their subsequent diagenetic transformation in the sediment" (Hupfer & Lewandowski, 2008 and citations therein).

Among the phytoplankton or benthic species that proliferate in aquatic environments, some cyanobacteria and microalgae emit toxins that make fresh water unsuitable for drinking water production (Griffith & Gobler, 2020; Myer et al., 2020; Paerl et al., 2001; Wells et al., 2021). In marine waters, the consumption of shellfish and fisheries resources is usually threatened by the presence of toxic phytoplankton (Anderson et al., 2002). Planktonic toxins may also have adverse impacts on the health of species inhabiting aquatic ecosystems (mammals, fishes, and invertebrates). In addition to their significant biomass following their proliferation, certain species of microalgae exude organic molecules (foam) that are added to the stock of organic matter produced in the water (Desroy & Denis, 2004).

Although this is not depicted in Figure 1, the threat to ecosystem services (e.g., drinking water, irrigation and fishing) has become an important argument for raising awareness in society about the preservation of aquatic ecosystems, see fig. 2 in Lundberg (2005). Beyond the threat to the preservation of ecosystems and their biodiversity, nutrient pollution is a matter of public health, and the growing need for drinking water has led to the construction of reservoirs, many of which suffer from nutrient pollution (Oliver et al., 2019). This issue has given rise to a whole literature on water treatment, in particular related to the presence of toxins produced by the blooms of cyanobacteria (He et al., 2016).

The distinction between direct and indirect effects finds its limits when the trophic state integrates autotrophic and heterotrophic components of the ecosystem (Dodds, 2006; Dodds & Cole, 2007). Changes in primary producers affect higher trophic levels (Deegan et al., 2002). For example, the development of macroalgae mats can be accompanied by a proliferation of grazers, to the detriment of other invertebrate species (Norkko & Bonsdorff, 1996).

As outlined in a general way by Odum (1969), there is a close link between the trophic state and the degree of stability of an ecosystem. Each ecosystem has its own trajectory, which can go through phases of stabilization and stress depending on natural and anthropogenic constraints. Most oligotrophic ecosystems, such as remote forests and lagoons or shallow lakes (where light reaches the bottom), may see their biomass (and therefore their stock of nutrients) increase. This biomass is not quickly recyclable because it is integrated into slow-growing species (good nutrient conservation) (Odum, 1985). Some oligotrophic ecosystems, such as peat bogs, can accumulate organic matter as detritus, but the latter has a low rate of recycling because the chemistry of the environment limits the activity of microorganisms. Increased availability of nutrients affects the entire food web of the ecosystems by inducing subsidy effects in the first phase (Odum et al., 1979), followed by a second phase of simplification of their structure and functions toward the development stage (Odum, 1985). Additionally, an ecosystem under stress tends to release nutrients, which means that eutrophication is a process that often accompanies other pathways of ecosystem alteration. Therefore, eutrophication cannot be reduced to a simple chain of causes with nutrient pollution as the sole cause.

Clearly, eutrophication has several causes, involves many species and affects the entire ecosystem. The essential part is to know to what extent it is possible to write a definition of the process of eutrophication that is at the same time rigorous and generic, and which is shared by the whole scientific community. Finding the few words that could integrate all the processes involved in eutrophication therefore remains a real challenge. The urgency of safeguarding ecosystems from nutrient pollution constitutes a second challenge, making it necessary to provide an educational framework to ecosystem managers and society.

METHODS

Search for definitions

Bibliographic tools using search equations and simple keywords, such as Web of Science, list thousands of publications dealing with eutrophication, but they do not tell us whether they contain a definition. The inefficiency of such equations in selecting articles of interest is because search equations do not allow searching for words in the text body of the articles and most authors have a definition of eutrophication in the introduction of the article and not in the summary, at least when this research was carried out. Google Scholar allows searching for an exact string of words (in quotation marks) within the text body of most academic journals, books, lectures, theses, master reports, and technical reports. In 2014, of the 114 million English scientific documents available on the internet, 88% were accessible via Google Scholar (Khabsa & Giles, 2014). Some authors have even found 100% coverage by Google Scholar when searching for clinical trials and bibliographic summaries (Gehanno et al., 2013). Google Scholar is one of the most complete academic search engines, with the largest scope and sources and almost 400 million records (Gusenbauer, 2019, 2022). Strings of words referring to a definition of eutrophication were used with strings like "eutrophication is defined," "define eutrophication as" or "eutrophication refers to" (list in Appendix S1: Table S1).

We collected definitions in the literature according to the following criteria: (1) The definition came from a scientific article published in a peer-reviewed journal and from a scientific or educational book (higher education only) or from a report, directive, glossary or website produced by a national or international organization; (2) nested citations were taken into account when the author(s) modified the original definition; (3) the definition could include several sentences as long as the author(s) talked about one of the categories of descriptors (Figure 1). It was sometimes difficult to characterize the limits of the definitions. Some authors gave a concise definition but then changed the subject in the following sentences. Others described the eutrophication process in much of their introduction. In addition, many authors did not necessarily use the word "define" or "definition" but only "eutrophication is" (Appendix S1: Table S1). Finally, considering the authors' wish to characterize the process, their description of eutrophication was considered as a definition.

Analysis of definitions

Collecting and organizing information

Each definition (see listing in Pannard, 2024a at https://doi.org/10.6084/m9.figshare.24004110) was studied by analyzing the context of its publication and the words that it contained (most used words). To harmonize the definitions, a survey form was independently filled out for each definition by two experts (Appendix S1: Section S1). The form included questions about the extrinsic and intrinsic descriptors. Extrinsic descriptors were the publication date and the part of the land–sea continuum involved in the definition or in the document. Intrinsic descriptors were used to characterize and analyze the definition content related to the three process categories: *causes*, *direct effects* and *indirect effects* depicted in Figure 1, also considering the consequences of eutrophication for ecosystem services (Box 1).

Considering the circumstance that the underlying meaning is more important than the exact word used, some words were grouped around a single term. For example, the words "cultural," "artificial," and "manmade" were regrouped under the term "anthropogenic" in the descriptor "time scale" (Box 1). After verification of the coincidence of answers by the two experts, the results of the survey forms were gathered into a table with one definition per row.

Data analyses

To characterize the typical content and the most used terms in the eutrophication definitions, the most common terms in the definitions were identified by their frequency of use.

To see how the definitions are distributed in the descriptors' space, an MCA was applied to the data (available online in Pannard, 2024b at https://doi.org/10.6084/m9.figshare.24004113). MCA is suitable for the analysis of qualitative data from surveys and is regularly used successfully in health science (Costa et al., 2013; Kremer et al., 2020), economy (Parchomenko et al., 2019),

BOX 1 Intrinsic descriptors and terms used to break down and analyze the definitions. Each descriptor contains nonexclusive terms that describe the definition. The other words grouped under the same term are mentioned in italics

1. Intrinsic descriptors and terms used **for the causes:**
   - **Time scale:**
     - Natural
     - Anthropic (*cultural, artificial, manmade*)
     - Natural and anthropic
   - **Nutrient type:**
     - Nitrogen
     - Phosphorus
     - Nitrogen and phosphorus
     - Nutrient
     - Minerals, silicates, trace elements, potassium, micronutrients
   - **Nutrient form:**
     - Inorganic (except N_2)
     - Organic
     - Inorganic and organic
   - **Environment factors:**
     - Light
     - Temperature
     - Hydrodynamic (*residence time, stratification, tides, confinement*)
2. Intrinsic descriptors and terms used **for the direct effects:**
   - **Primary producers (PP) types:**
     - Plant (*higher, vascular*)
     - Phytoplankton (*microalgae*)
     - Macroalgae
     - Algae
     - Primary producer (*autotroph*)
     - Vegetation (*vegetal*)
     - Cyanobacteria
   - **PP responses:**
     - Increased growth rate (*production, productivity*)
     - Increased biomass (*proliferation, increased number*)
     - PP community change
     - Turbidity (*transparency, light*)
3. Intrinsic descriptors and terms used **for the indirect effects:**
   - **For ecosystem:**
     - Biodiversity loss
     - Oxygen depletion
     - Toxicity
     - Nutrient cycle
     - Habitat
     - Heterotrophic community
     - Physical (*volume, water depth, currents, integrity, silting up*)
     - Other: repercussions on the matter and energy balance, whole-system heterotrophic or autotrophic metabolism, negative environmental effects, accelerated extinction of a body of water, decreased volume, die-off of benthic animals, benthic mortality, loss of submerged aquatic vegetation
   - **For society:**
     - Water quality
     - Ecosystem service (*odor, aesthetics, clogging, navigation*)

social sciences (Davidescu et al., 2020) and many other fields (Beh, 2004). This method of geometric data analysis is close to factorial correspondence analysis (CA), which is used for quantitative or semiquantitative data. The MCA was done with the RStudio software (packages ADE 4 and vegan) (R Core Team, 2019). The content of definitions was described through the set of qualitative data (association of terms from the different descriptors). The MCA mapped the dispersion of the definitions (their variability in content) in a multidimensional space with maximization of the variance in the first plane (axes 1 and 2) and yielded correlations between the new factorial axis and the initial variables (descriptors). The MCA identifies the associations of terms in the definitions by positioning the observations in the space of variables (descriptors and terms; Box 1). Only the first two axes carrying a maximum of variance (eigenvalues) were analyzed (Figure 2). Projection plots of definitions are shown individually for each variable (descriptor) but can all be superimposed. For each descriptor (the individual plot), definitions containing the same term were grouped in ellipses that were attached to the barycenter of the data point cloud of the term.

Further, Between-Class Analyses (BCA) performed on the MCA were used to separate groups of definition, with the "bca" function in ADE4. This allowed us to test their significance through permutation tests (Thioulouse et al., 2018). Publication date, document type and ecosystem type could thus be tested by BCA to see if the definition changed significantly depending on time, document type or ecosystem.

The Rscript is available online (Pannard, 2024d) on Figshare at https://doi.org/10.6084/m9.figshare.24004119 with the associated csv file in Pannard (2024c) at https://doi.org/10.6084/m9.figshare.24004116.

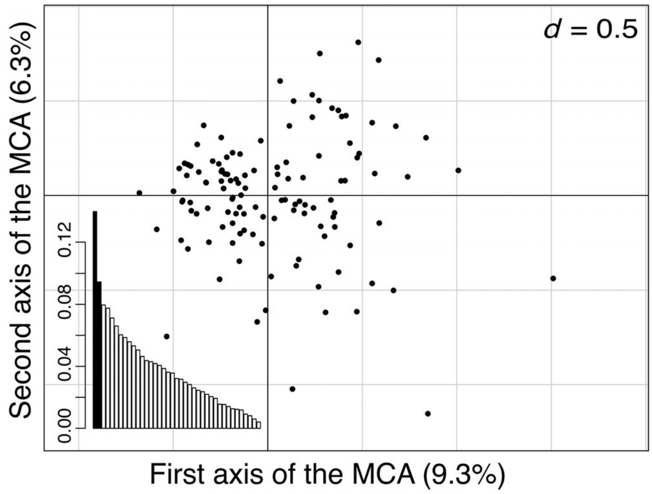

FIGURE 2 Projection plot of the first two axes (constituting 15.6% of the total variability of the dataset, i.e., inertia) of the multiple correspondence analysis (MCA). Each point is a definition of eutrophication in the space of variables, which will be analyzed further (see Figure 5). Plot scale is demonstrated by the grid whose size is given by the *d* value in the upper right corner. The bar chart of the eigenvalues is shown in the bottom left corner, with black bars for the first two axes.

RESULTS

Extrinsic descriptors

Time distribution

We found 138 definitions, the oldest dating back to 1947 and dedicated to lakes (Hasler, see Table 1 for definitions cited in the text). For coastal waters, the word eutrophication was first mentioned in 1971 by Ryther and Dunstan (1971), while the first definition involving marine ecosystems appeared in 1974 (Steele, 1974). We observed an increase in the number of definitions over time, which was marked by three peaks (Figure 3). The first peak was close to 1970 and was mainly associated with freshwater definitions. The second one occurred in the years 1995 to 2001 with definitions less specifically dedicated to freshwater ecosystems. The third peak was in the years 2007–2011. From 2000 onwards, definitions devoted to terrestrial eutrophication appeared (Rodríguez & Macías, 2006), no. 71 for Koskela et al. (2007) in https://doi.org/10.6084/m9.figshare.24004110. In the MCA, the oldest definitions (before 1980) tend to be positioned to the right of the second axis, even if time period was not significant (Figure 4a; Monte Carlo test, $p > 0.05$).

Ecosystem type

The definitions of eutrophication for marine ecosystems are as numerous as those dedicated to freshwater ecosystems, and these two types together account for more than 80% of the total number (Table 2; Ecosystem type). A little more than 10% do not specify the type of ecosystem concerned. Most definitions originate from papers dealing with aquatic ecosystems, but two of them are dedicated to terrestrial ecosystems. Finally, like time, ecosystem type was not a significant clustering factor (Figure 4b; Monte Carlo test, $p > 0.05$).

Document type

More than 70% of the definitions of eutrophication appeared in scientific journals and books, while the

TABLE 1 Examples of definitions.

Author(s)	Definition
Andersen et al. (2006)	Accepting the above suggestions allows a definition of eutrophication as "The enrichment of water by nutrients, especially nitrogen and/or phosphorus, and organic matter, causing an increased growth of algae and higher forms of plant life to produce an unacceptable deviation in structure, function and stability of organisms present in the water and to the quality of water concerned compared with the reference condition."
Ansari et al. (2010)	Eutrophication is the natural process driving the ecological succession of freshwater, estuarine, and marine ecosystems.
Art (1993)	The process by which a body of water acquires a high concentration of nutrients, especially phosphates and nitrates. They typically promote excessive growth of algae. As the algae die and decompose, high levels of organic matter and the decomposing organisms deplete the water of available oxygen, causing the death of other organisms such as fish.
Bricker et al. (2008)	Eutrophication is a process in which the addition of nutrients (largely nitrogen and phosphorus) to water bodies stimulates algal growth. Excessive nutrient inputs may lead to other more serious problems such as low dissolved oxygen and loss of submerged aquatic vegetation (SAV).
Business Dictionary No. 1 (accessed 2018)	Slow-aging process during which a bay, estuary, lake, river, stream, or other shallow body of water deteriorates into a bog or marsh, and eventually dies.
Cambridge Dictionary (accessed 2019)	The addition of nutrients to water in lakes and rivers, which encourages plant growth that can take oxygen from the water and kill fish and other animals.
Carpenter (2005)	Eutrophication (the overenrichment of aquatic ecosystems with nutrients leading to algal blooms and anoxic events).
Carpenter et al. (1998)	Eutrophication means the fertilization of surface waters by nutrients that were previously scarce.
Claussen et al. (2009)	Eutrophication (nutrient enrichment and subsequent processes).
Cloern (2001)	In this review I use the word eutrophication in a more general sense to reference the myriad biogeochemical and ecological responses, either direct or indirect, to anthropogenic fertilization of ecosystems at the land–sea interface.
Cloern et al. (2013)	Eutrophication is a syndrome of ecosystem responses to human activities that fertilize water bodies with nitrogen and phosphorus, often leading to changes in animal and plant populations and degradation of water and habitat quality.
Díaz et al. (2010)	Eutrophication is the leading cause of water quality impairment around the world. It is the overenrichment of water with nutrients such as nitrogen and phosphorus as a result of human activity. Eutrophication can be defined simply as the increase in the rate of production and accumulation of organic carbon, which is more than what an ecosystem is normally adapted to processing (Nixon, 1995; Rabalais, 2004). Eutrophication can be harmful to both freshwater and marine ecosystems, and leads to a progression of symptoms that include (Selman et al., 2008): Excessive phytoplankton and macroalgal growth that is the source of organic carbon for accumulation. This can also reduce light penetration and lead to a loss of submerged aquatic vegetation (SAV). An imbalance of nutrient ratios that can lead to a shift in phytoplankton species composition and create conditions that are favorable to nuisance and toxic algal blooms. Harmful algal blooms (HABS) can cause kills of living marine resources and shellfish poisoning in humans. Changes in species composition and biomass of the benthic (bottom-dwelling) community; eventually leading to reduced species diversity and increased dominance of gelatinous organisms such as jellyfish. Low dissolved oxygen and formation of hypoxic or dead zones (oxygen-depleted waters). These oxygen-starved areas stress aquatic ecosystems, often leading to kills of living marine resources, altered ecosystem energy flows, and in severe cases ecosystem collapse.
Dodds (2007)	Eutrophication is the increase in factors that move a system toward a eutrophic state.
Ferreira et al. (2011)	Eutrophication is a process driven by the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus leading to: increased growth, primary production, and biomass of algae; changes in the balance of organisms; and water quality degradation. The consequences of eutrophication are undesirable if they appreciably degrade ecosystem health and/or the sustainable provision of goods and services.

(Continues)

TABLE 1 (Continued)

Author(s)	Definition
Gooday et al. (2009)	Eutrophication: nutrient enrichment leading to elevated production of particulate organic matter and in some cases hypoxia.
Hasler (1947)	In this paper eutrophication will be interpreted in the broadest sense; namely, lake enrichment owing to any and all nutritive substances.
Justić Rabalais and Turner (1995)	Eutrophication, the high productivity resulting from nutrient enrichment and often manifested in noxious phytoplankton blooms, oxygen depletion, and benthic mortality, has been reported from a variety of coastal marine ecosystems.
Le et al. (2010)	Lake water eutrophication is changes in water chemical properties triggered by the accumulation of excessive nutrients such as nitrogen and phosphorus. It is a joint byproduct of light, heat, and hydrodynamics resulting from a series of biological, chemical, and physical processes. Water eutrophication can lead to rapid production of phytoplankton and other microorganisms and deterioration of water quality, both of which are detrimental to aquatic ecology and the normal functioning of water bodies (OECD, 1982). Subsequently, the lake ecosystem is destroyed and the functionality of the water is weakened. In the worst case, eutrophication can result in frequent outbreaks of algal blooms, which threatens a reliable supply of drinking water.
Nitrate European commission Directive (1991)	Eutrophication is enrichment of water by nitrogen compounds, causing accelerated growth of algae and higher forms of plant life, thereby producing an undesirable disturbance of the balance of organisms present in the water and the quality of the water concerned.
Nixon (1995)	Eutrophication is an increase in the rate of supply of organic matter to an ecosystem.
Parma (1980)	Eutrophication is the process in water during which the factors stimulating autotrophic production become optimal. In this definition the essentials are: (a) it subscribes to the original concept of NAUMANN; (b) eutrophication is a process in water; (c) not only nitrogen and phosphorus but also light, temperature, trace elements, plant hormones, and so forth. enhance eutrophication; (d) eutrophication deals with an optimizing rather than with an enrichment process; increasing temperature and light stimulate autotrophic production; however, when a certain optimum has exceeded a retardation of the process may occur and the system does not longer eutrophicate; (e) eutrophication factors are the ones that stimulate autotrophic production; (f) a human influence is not essential for eutrophication; natural eutrophication (P-loading via seepage) and cultural eutrophication (P-loading via a sewage purification plant) may be distinguished.
Rabalais (2004)	The increase in carbon production and carbon accumulation in an aquatic ecosystem.
Rast and Holland (1988)	Eutrophication is defined as "the nutrient enrichment of waters which results in the stimulation of an array of symptomatic changes, among which increased production of algae and macrophytes (aquatic plants), deterioration of water quality and other symptomatic changes, are found to be undesirable and interfere with water uses."
Rodríguez & Macías (2006)	In soils, eutrophication is indicated by an increase in the productivity rates of ecosystems, followed by nutritional imbalances in plants and, in the worst cases, their disappearance or substitution by other type of vegetation.
Sathananthan (2016)	Eutrophication: The process by which a body of water acquires a high concentration of nutrients, especially phosphates and nitrates. These typically promote excessive growth of algae. As the algae die and decompose, high levels of organic matter and the decomposing organisms deplete the water of available oxygen, causing the death of other organisms, such as fish. Eutrophication is a natural, slow-aging process for a waterbody, but human activity greatly speeds up the process (Art, 1993). It may occur naturally but can also be the result of human activity (cultural eutrophication from fertilizer runoff and sewage discharge) and is particularly evident in slow-moving rivers and shallow lakes. Increased sediment deposition can eventually raise the level of the lake or river bed, allowing land plants to colonize the edges, and eventually converting the area to dry land." (Lawrence & Jackson, 1998).
Smith et al. (1999)	Eutrophication is the process by which water bodies are made more eutrophic through an increase in their nutrient supply.

TABLE 1 (Continued)

Author(s)	Definition
Steele (1974)	Eutrophication: The increase in plant growth rate resulting from an increased rate of nutrient supply. Whereas phosphorus is a major problem in freshwater, nitrogen addition appears to be the critical factor in the sea. The addition of nutrients by man is usually called "cultural" eutrophication.
Urban Waste Water Treatment Directive (EE 1991)	Eutrophication means the enrichment of water by nutrients, especially compounds of nitrogen and phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms and the quality of the water concerned.
Zhang et al. (2011)	Eutrophication can be defined as an intensified accumulation of diatom biomass that is generally due to an increase in nutrients (primarily phosphorus and nitrogen).

remaining were retrieved from documents on management and communication (Table 2; Document type). In the MCA, the type of document was the only significant grouping factor among those dealing with extrinsic descriptors (Monte Carlo test, $p = 0.001$; Figure 4c). The definitions from scientific documents (articles, books) tend to be positioned to the left of axis 1 and the others to the right, in particular the two definitions from European Union directives (Nitrate EC Directive, 1991; Urban Waste Water Treatment EC Directive [UWWT Directive], 1991).

Intrinsic descriptors

Categories

All combinations of the three categories of descriptors (cause, direct and indirect effects) can be found in the panel of definitions, except indirect effects alone (Table 3). The definitions citing the three categories, like Carpenter (2005) and Claussen et al. (2009), belong to the largest set (59%). The only definition of eutrophication that does not define nutrients as a cause but ascribes it to the evolution of aquatic ecosystems over geological time is that of Business Dictionary No. 1 dedicated to natural eutrophication.

Nixon (1995) only refers to direct effects, similar to 4% of the definitions (Table 3). Only one definition does not cite any of the categories (Ansari et al., 2010; Table 1). On the projection plots from the MCA (Figure 5a–c), definitions not mentioning categories are grouped to the left of axis 1, while definitions citing them are generally grouped to the right.

Causes

The time scale makes it possible to distinguish natural eutrophication from anthropogenic eutrophication, but it is mostly unspecified (Table 4; time scale). Definitions referring to or including natural eutrophication represent 6% of the corpus and are mostly positioned to the left of axis 1 in the MCA (Figure 5d). The term "nutrient," mentioned in 86% of the definitions, is the most frequent. However, no chemical element is cited for most definitions (Table 4; nutrient type). N and P are cited in 37% of the definitions but only associated with DSi or minerals in 2% of the definitions. One definition refers to N alone (Nitrate EC Directive 1991) and only one to P alone (Bennion et al., 1996) (see Pannard, 2024a at https://doi.org/10.6084/m9.figshare.24004110). These last two definitions clearly appear as exceptions on the MCA projection plot (Figure 5e). For almost 90% of the definitions, the nutrient form (inorganic or organic) is not specified (Table 4; nutrient form). The only five definitions citing organic nutrients tend to be positioned to the right of axis 1 (Figure 5f). Most definitions do not cite environmental factors as the cause of eutrophication (Table 4, environmental factors). The only two definitions citing light and temperature (Le et al., 2010; Parma, 1980) are discriminated in the MCA plot (Figure 5g). The only two other definitions referring to depth (siltation, filling) are also discriminated in the MCA (Kitsiou & Karydis, 2011; Sathananthan, 2016) (see Pannard, 2024a at https://doi.org/10.6084/m9.figshare.24004110). An increase in water transparency or a decrease in turbidity never appears as a cause in the definitions, even in marine definitions where light may be the limiting factor. Further, changes in top–bottom cascading control are never cited as a cause of eutrophication in the collected definitions.

Direct effects

There is a great diversity of primary producers cited in the definitions even if most of them do not specify them (Table 5; Primary producer type). When primary

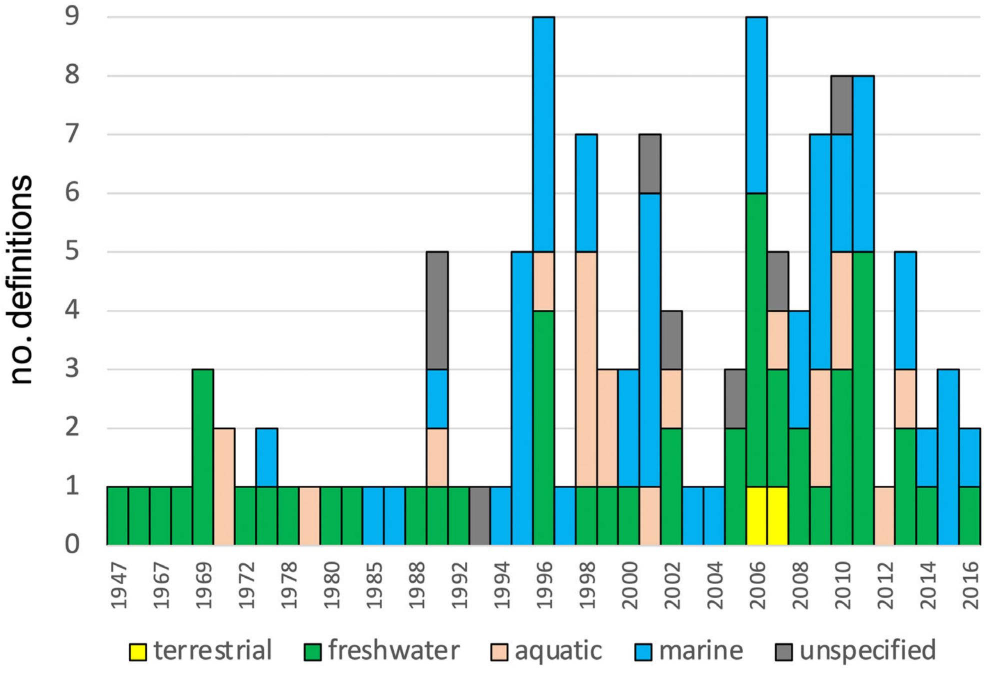

FIGURE 3 Evolution from 1947 to 2016 of the number of definitions of eutrophication with an indication of the type of ecosystem concerned (15 definitions are not included as they originated from undated glossaries and websites).

producers are specified, it is mainly with the word *algae* (36%: 20% alone and 16% in association with another primary producer). The word *plant* is used in 36% of the definitions to identify the type of primary producer (20%) or as an adjective to specify the nature of nutrients (plant nutrients) or biomass (plant biomass). Only 10% of the definitions cite phytoplankton and 4% cyanobacteria as primary producers, with only one definition referring specifically to diatoms (Zhang et al., 2011). MCA projections show that definitions specifying the type of primary producer tend to cluster to the right of axis 1 (Figure 5h–l).

In the response of primary producers, the term *growth* (including the words *production* and *productivity*) is used in 59% of the definitions (Table 5; Primary producer responses), with about one-half associated with an adjective synonymous with excess (e.g., excessive, dense, luxuriant and nuisance) and another half with a verb meaning stimulation (e.g., enhanced, increased, and accelerated). The word *biomass* is present in 10% of the definitions, most often associated with a word specifying its origin (e.g., plants, algae, and phytoplankton). The definitions citing growth and biomass are not discriminated by the MCA (Figure 5n). Definitions invoking a change in the composition of primary producers or an increase in turbidity as a direct effect are seldom (Table 5; Primary producer response) and are positioned to the right of axis 1 in the MCA plot (Figure 5p).

Indirect effects

Indirect effects of eutrophication on ecosystems are cited in around 40% of the definitions (Table 6; Ecosystems). The most cited indirect effect is a decrease in oxygen concentration (27%). Changes in heterotrophic communities, decrease in biodiversity and alteration of water quality (Table 6; see Society) are cited in more than 10% of the definitions. Numerous other indirect effects (Box 1) are quoted and found in 18% of the definitions. In the MCA, the definitions specifying indirect effects tend to group to the right of the axis (Figure 5q–z). Some definitions include direct and indirect effects using general terms like *symptoms* (Rast & Holland, 1988). Cloern (2001) also integrates direct and indirect effects into his definition using the term "response" of an ecosystem to nutrient inputs from human sources. The term *syndrome* appeared only recently in two definitions (Cloern et al., 2013; Dokulil & Teubner, 2010).

Analysis of the semantic landscape of definitions

A definition of eutrophication made from the most frequently used terms in the collected definitions would be "an enrichment of inorganic nutrients leading to the increase in the growth of algae and multiple indirect consequences, in particular a decrease in oxygen

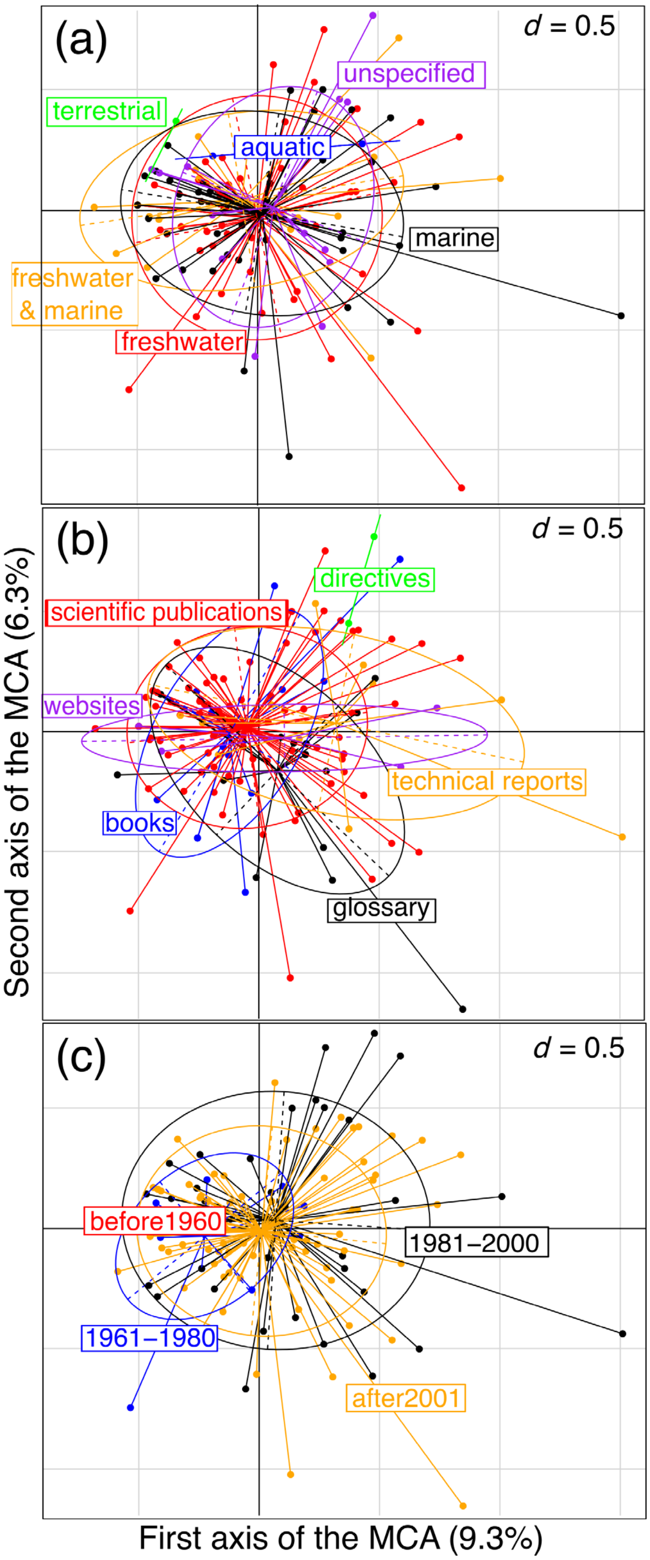

FIGURE 4 Projection plots of the first two axes of the multiple correspondence analysis (MCA) on the definitions of eutrophication: The projection of the definitions is shown with groups associated with (a) their origin (marine, freshwater, terrestrial), (b) source and (c) time period. Unspec: unspecified. Plot scale is demonstrated by the grid whose size is given by the *d* value in the upper right corner.

TABLE 2 Repartitioning of the definitions depending on their extrinsic descriptors. Due to rounding, the sum does not always equal 100%.

Descriptor	Percent
Ecosystem type	
Freshwater	36
Marine	35
Freshwater and marine	13
Unspecified	12
Aquatic	2
Aquatic and terrestrial	1
Lakes, estuaries, and streams	1
Soil	1
Document type	
Scientific article	62
Glossary	13
Scientific book	12
Technical report	9
Website	3
Directive	1

TABLE 3 Repartitioning of the definitions depending on intrinsic descriptors. Due to rounding, the sum does not equal 100%.

Descriptor type	Percent
Causes + direct effects + indirect effects	59
Causes + direct effects	23
Causes	10
Direct effects	4
Direct effects + indirect effects	1
Causes + indirect effects	1
None	1

concentration." This definition contains the main terms of the three descriptors (Box 1) such as those of Gooday et al. (2009) and the Cambridge Dictionary, which appear close to the origin of the MCA axes (Figure 6). However, most definitions are far from this central position. There is a very diverse combination of terms resulting in a slight dispersion of definitions, with the extreme of some having no word in common at all (Ansari et al., 2010; Carpenter et al., 1998). Axis 1 tends to discriminate between definitions according to the degree of citation of the terms identified in Box 1. On the far left, Ansari et al. (2010) summed up eutrophication as a natural process, while on the far right Dìaz et al. (2010) cited almost all the terms in Box 1. On axis 2, the definitions are mainly distributed according to their content of indirect effects. Those referring to effects on the ecosystem are located at the bottom (Sathananthan, 2016), while those dealing with the effects

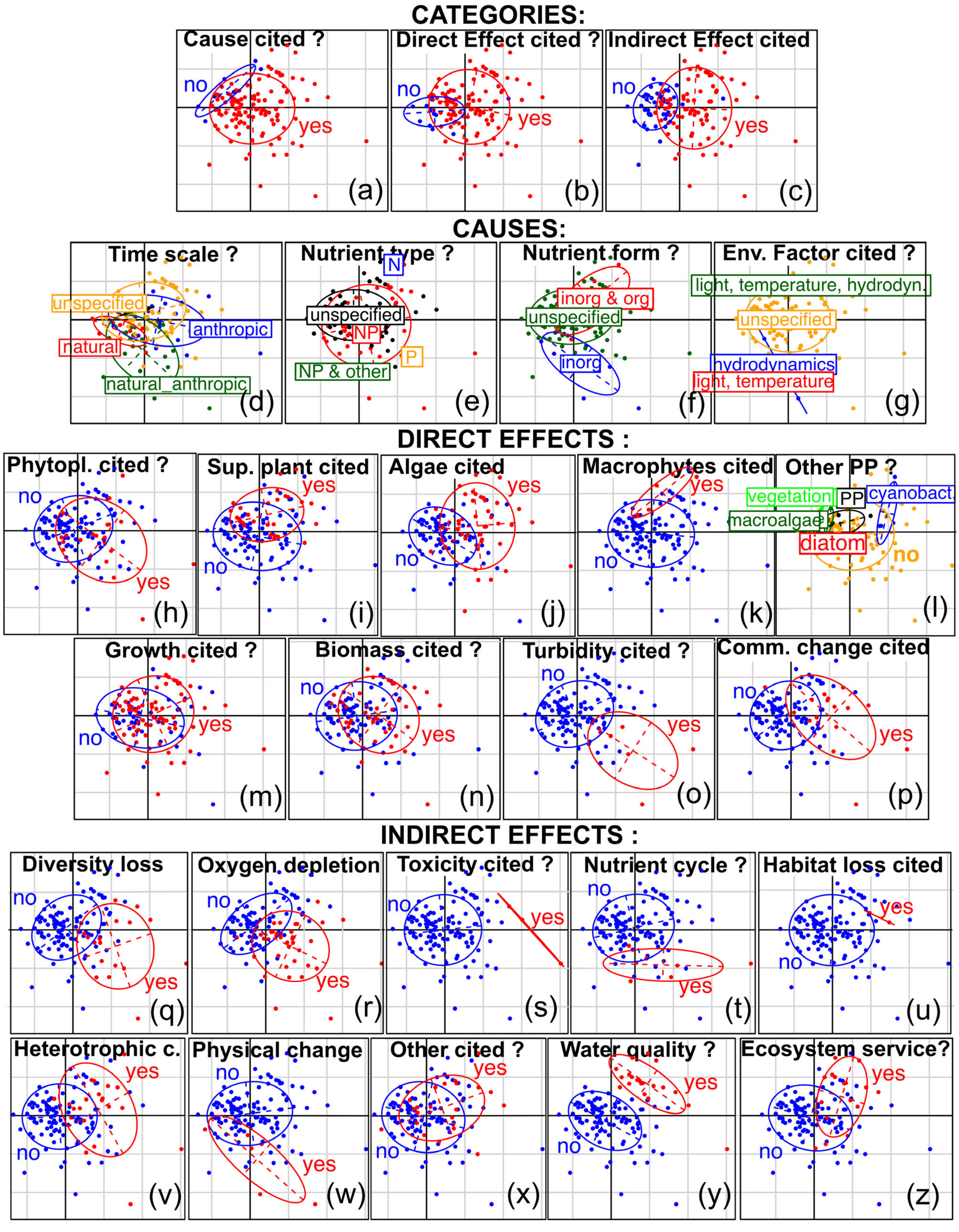

FIGURE 5 (a–z) Projection plots of the first two axes (constituting 15.6% of the total variability of the dataset, i.e., inertia) of the multiple correspondence analysis (MCA) on the definitions of eutrophication: projections of each variable (definition content: "yes" means that it is cited and "no" that it is not) in the definitions space. Plot scale is demonstrated by the grid whose size is 0.5.

TABLE 4 Repartitioning of the definitions by category of causes. Due to rounding, the sum does not always equal 100%.

Causes	Percent
Time scale	
Unspecified	64
Anthropic	15
Natural and anthropic	14
Natural	6
Nutrient type	
Unspecified	59
Nitrogen + phosphorus	37
Nitrogen	1
Phosphorus	1
Nitrogen + phosphorus + potassium	1
Nitrogen + phosphorus + minerals	1
Nitrogen + phosphorus + silicate	1
Nitrogen + phosphorus + micronutrients	1
Nutrient form	
Unspecified	86
Inorganic	9
Inorganic + organic	5
Environmental factor	
Unspecified	97
Hydrodynamics	1
Light + temperature	1
Light + temperature + hydrodynamics	1

TABLE 5 Repartitioning of the definitions by category of direct effects. Due to rounding, the sum does not always equal 100%. Definitions could use several terms, leading to a total of >100%.

Direct effects	Percent
Primary producer type	
Unspecified	38
Algae	20
Plant	9
Phytoplankton	7
Plant + algae	7
Algae + cyanobacteria	3
Vegetation	3
Algae + primary producers	1
Macroalgae	1
Primary producers	1
Algae + macrophytes	1
Algae + phytoplankton	1
Algae + plankton	1
Bacteria + plants	1
Diatoms	1
Macrophytes + algae + cyanobacteria	1
Macrophytes + phytoplankton	1
Phytoplankton + plants	1
Plants + macroalgae + algae + waterweeds	1
Plants + macrophytes + algae	1
Plants + primary producers	1
Plants + vegetation	1
Primary producer responses	
Increased growth rate + production + productivity	59
Increased biomass + proliferation + increased number	26
Unspecified	23
Change in autotrophic community	12
Turbidity + transparency + light + shading	4

on society are positioned at the upper end of the plot (Rast & Holland, 1988, Nitrates European Commission Directive 1991).

The MCA identified three groups of definitions (Monte Carlo test, $p = 0.001$; Figure 6). The first group, positioned to the left of axis 1, contains 72 definitions (52%) and includes mostly definitions from scientific publications (Figure 4b). Group 1 contains definitions citing the fewest descriptors (Figure 5a–c) and therefore the shortest (Claussen et al., 2009; Dodds, 2007; Nixon, 1995; Rabalais, 2004; Smith et al., 1999). References not citing any category are positioned at the far left of axis 1 (Ansari et al., 2010; Figure 6), and they include definitions related to natural and terrestrial eutrophication (Business Dictionary No. 1, 2018; Rodríguez & Macías, 2006). When direct effects are cited, they are often linked to the growth of primary producers without specifying their composition. However, Zhang et al. (2011), citing diatoms, are in group 1 (Figure 6). The 4% of definitions citing direct effects only occur in group 1, including those of Nixon (1995) and Rabalais (2004). In group 1, the vast majority of definitions do not mention indirect effects.

The 42 definitions of group 2 are distributed among the different types of documents (Figure 4b). Group 2 has a barycenter closer to group 1 than group 3 (barycenter right of axis 1 and below axis 2 in Figure 6). Unlike group 1, the definitions of group 2 tend to cite the type of primary producer. Group 2 contains definitions citing community change and turbidity as direct effects (Figure 5o,p). Indirect effects on the ecosystem are cited in 94% of the group 2 definitions (Figure 5q–t). Group 2, which includes the longest and most detailed definitions (Díaz et al., 2010; Sathananthan, 2016), is the most dispersed group on the MCA projection.

The 24 definitions of group 3, whose barycenter is to the right of axis 1 and above axis 2, are quite distinct from the other two groups. Group 3, similar to group 2, tends to specify the type of primary producer (Figure 5h,i). The three definitions citing cyanobacteria belong to group 3. Unlike group 2, the indirect effects cited in group 3 are mainly related to water quality and ecosystem services (Figure 5y,z) like Le et al. (2010). Group 3 includes definitions of European directives on water quality (Andersen et al., 2006; Ferreira et al., 2011; Nitrates European Commission Directive 1991; Urban Waste Water Treatment EC Directive (UWWT Directive), 1991).

DISCUSSION

More than 40 years ago, Parma (1980) had already collected and analyzed eight definitions of eutrophication and found that some were based on the causes (increase in nutrients), while others were focused on the direct effects (increase in the biomass of autotrophs). He also noted a dichotomy between the definitions considering the process of eutrophication to be of human origin and those defining it as a process independent of anthropogenic activities. Finally, Parma (1980) underlined the difficulty of defining eutrophication due to the risk of creating confusion. The attempt to develop a unified definition of eutrophication is therefore not new and neither is the concern of multiple aspects of the term "eutrophication." Beyond the purely scientific aspect is the question of responding to regulatory and societal issues related to eutrophication, exacerbated by climate change. Indeed, the interest in tackling the topic was boosted by problems largely encountered by stakeholders in managing waterbodies for anthropogenic uses. However, identifying a consensual scientific definition of eutrophication is required but represents a challenge due to the complexity of processes.

The bibliographic tools used permitted us to identify articles on eutrophication. The search for word strings in the body text, essential for the collection of definitions, was made possible using Google Scholar (Gusenbauer, 2019, 2022). Definitions from technical reports (gray literature) were only partially acquired as they are not all available on the internet, not least because the peak of interest for the topic was in the 1990s. Yet, the integration of this data source would be valuable to make a complete overview of what is meant by "eutrophication" by the diversity of actors (from academic scientists to operational water managers) as it represents an important mass of documents not always validated by peers. Moreover, compiling this type of document across different countries in a sufficiently representative way is unfortunately not feasible, especially because the different languages should be considered.

The number of definitions is considerable, with major differences between them, making them almost unique (several have no words in common). Eutrophication is a concept of universal nature, existing both in a spatial (all ecosystems from boreal forests to oceans) and a temporal dimension (from geological time scales to specific events of both natural and anthropogenic origin). Eutrophication is also a multidisciplinary object of investigation that involves a large number of scientific disciplines (biology, geology, chemistry, water and environmental technology) and a vast number of approaches, from biogeochemical cycles (e.g., N, P, Si) to ecological successions. The definitions of eutrophication often depend on the issues addressed by the authors, whether they are academic scientists or in the field of operational application. The meaning of the word *eutrophication* can be top driven (study of the basic processes or of the mechanisms of incorporation of nutrients into the food web) or bottom driven (effects of global disturbances on the characteristics of ecosystems or ecosystem services). For example, for the European Nitrates Directive, nitrogen is involved only as a cause of eutrophication, and the directive does not address

TABLE 6 Repartitioning of the definitions by category of indirect effects. Definitions could use several terms, leading to a total of >100%. See Table 1 for other indirect effects.

Indirect effects	%
Ecosystem	
Unspecified	59
Oxygen depletion	27
Other	18
Heterotrophic community	16
Biodiversity loss	13
Nutrient cycle	5
Physical effects	4
Biological toxicity	2
Change in habitat	1
Society	
Unspecified	81
Water quality	7
Ecosystem service	5
Water quality + ecosystem service	7

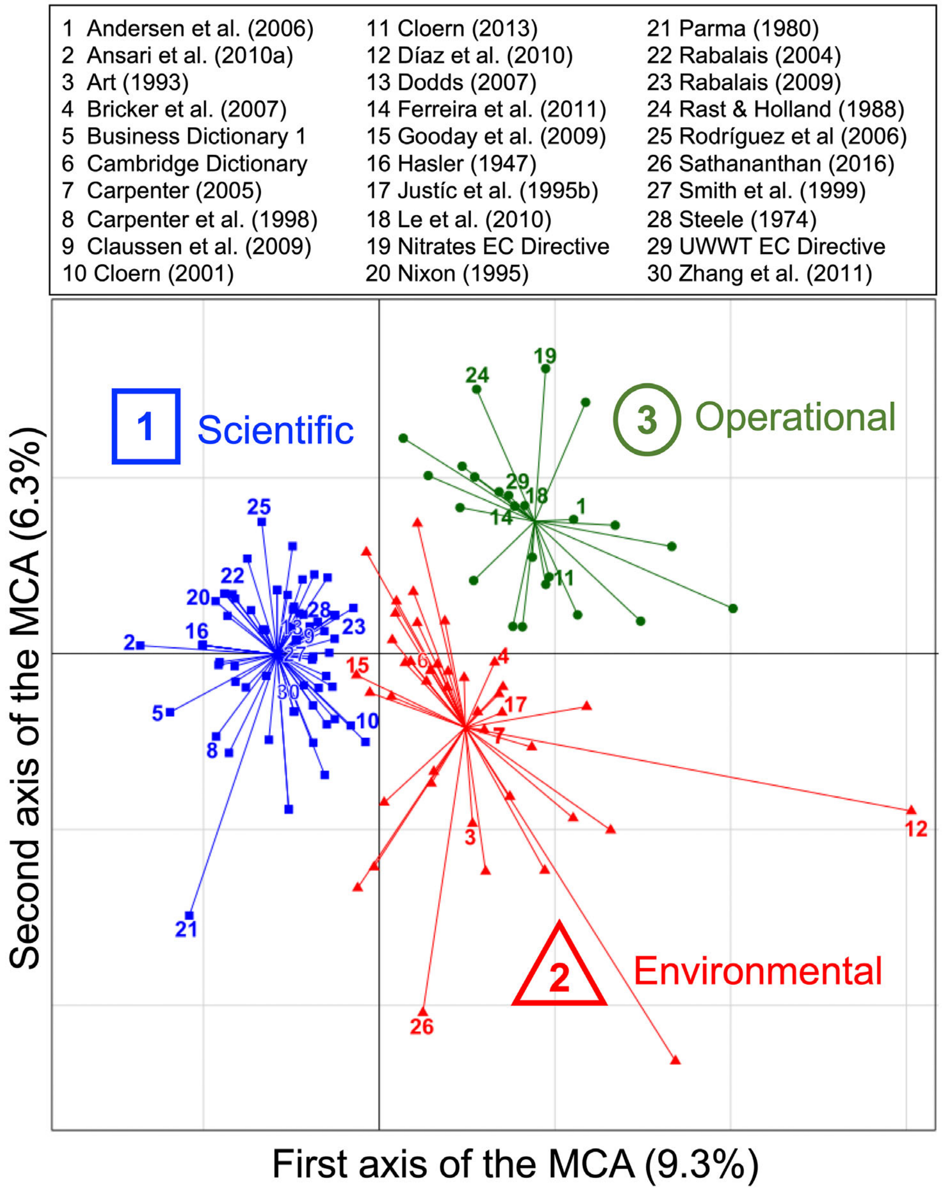

FIGURE 6 Projection plots of the first two axes (constituting 15.6% of the total variability of the dataset, i.e., inertia) of the multiple correspondence analysis (MCA) on the definitions of eutrophication: projection of the definitions in the space of variables. Three groups were identified ($p = 0.01$): (1) *scientific* definitions, (2) *environmental* definitions and (3) *operational* definitions. See text for details. Plot scale is demonstrated by the grid whose size is given by the *d* value in the upper right corner.

eutrophication but the impact of nitrate on water quality. The same bottom-driven effect applies to phosphorus in the European Urban Waste Water Directive.

The multiplication and dispersion of definitions can be partly explained by the transdisciplinary characteristics of eutrophication, which invites the authors to redefine what they understand by the word *eutrophication* under their scientific or technical discipline. Moreover, the definitions do not all have the same ambition of genericness. While Nixon (1995) dedicated his work to finding a definition, Zhang et al. (2011) defined eutrophication within the context of diatom communities. For managers, eutrophication can be defined through the phenomenon that worries them. The MCA distinguished three groups for understanding the dispersion of definitions, compiled under the themes *scientific*, *environmental*, and *operational*, which are discussed in detail in the following three paragraphs.

The *scientific* definitions

On the left of the first axis in Figure 6, group 1 brings together the definitions containing the fewest descriptors, coming mainly from scientific journals and books. Group 1 encompasses the oldest (before 1980), shortest and most generic definitions. Only one definition (Nixon, 1995), centered on the process itself (increased contribution of species with higher production-to-biomass ratio P/B), proved to be the only one meeting the requirements of a rigorous scientific definition. Rabalais (2004) modified Nixon's words but kept to the processes, with a comparable definition of "the increase in carbon production and carbon accumulation in an aquatic ecosystem." Even though group 1 contains definitions dedicated to natural eutrophication and to terrestrial ecosystems, some definitions apply to all ecosystems of the land–sea continuum and are independent of the time scale (Claussen et al., 2009; Dodds, 2007; Nixon, 1995; Rabalais, 2004). We qualify this group as "scientific" as it contains definitions that seek to describe the process in the most generic way possible (Table 1).

One of the most cited papers by Smith et al. (1999; cited 1909 in the Web of Science, 3755 in Google Scholar, July 2023) limits the causes of eutrophication to increase nutrient supply. However, regarding the consequences of bottom-up effects in food webs, limiting the causes of eutrophication to the increase in nutrient availability, the definition does not appear scientifically correct (Nixon, 1995; Östman et al., 2016). The Business Dictionary No. 1, which equates eutrophication with an aging process, is also not quite right because the ontogeny of an aquatic ecosystem can include both eutrophication and oligotrophication periods (Weber, 1907; Whiteside, 1983).

Scott W. Nixon is among the researchers who have devoted most of their career to eutrophication research on several aspects such as nutrient cycles (Nixon et al., 2008), environmental ecology (Nixon, 1988), impacts of human activities (Nixon, 1997), and indicators (Nixon et al., 2001). Nixon presented extensive thinking on how to define eutrophication, and his definition is one of the most cited in the literature (1808 in the Web of Science, 3390 in Google Scholar, July 2023). However, because Nixon (1995), new definitions have continued to be produced (Figure 3), sometimes referring to his definition. Nine definitions from the corpus incorporate Nixon's definition but in different ways. Castro and Freitas (2011), Greening and Janicki (2006) and Smith et al. (2003) quote Nixon (1995) without giving the content of the definition (respectively No. 28, 58 and 110 in Pannard, 2024a at https://doi.org/10.6084/m9.figshare.24004110). Ærtebjerg (2001, No. 1 in Pannard, 2024a at https://doi.org/10.6084/m9.figshare.24004110) faithfully reproduces Nixon's definition and adds a sentence directing the subject toward nutrient enrichment and its consequences for primary production. Bonsdorff et al. (1997, No. 18 in Pannard, 2024a at https://doi.org/10.6084/m9.figshare.24004110) removed the word "rate" from Nixon's definition, reducing the phenomenon to an increase in the production of organic matter. Rabalais (2004), Rabalais (2010), and Dìaz et al. (2010) further modified Nixon's definition by adding organic matter (or carbon) accumulation to increase production. In their review of eutrophication, van Beusekom (2018) and Malone and Newton (2020) highlighted the definition of Nixon and also that of Andersen et al. (2006).

All of these different ways of modifying and supplementing Nixon's definition probably mean that there are differences in how we understand and interpret what Nixon expressed by "an increase in the rate of supply of organic matter." The word *rate* implies that eutrophication is not only an increase in primary production. Increased production could be simply linked to the phenology of the species (e.g., seasonal or day/night variations). The accumulation of carbon in an ecosystem does not characterize eutrophication alone (e.g., peat bogs). Nixon's phrase suggests an increase in the ratio of production (P in grams per square meter per year) to biomass (B in grams per square meter), which would literally mean an increase in productivity. Fifteen definitions in the dataset contain the word *productivity*. However, it is not certain that all authors agree on a single meaning of the word *productivity*, and some of them, if not most, confuse it with *production* (see e.g., Justić, Rabalais, Turner & Dortch, 1995). Additionally, there are several ways to express the P/B ratio according to the units of space (areal or volumetric), of time (hour, day, year) and of biomass (carbon or chlorophyll *a*). Moreover, a generic model linking the P/B ratio to the structure and functioning of ecosystems has yet to be established (Baird et al., 1991; Banse & Mosher, 1980; Jenkins, 2015). Finally, even if Nixon has largely paved the way, there is still work to do to achieve a successful scientific definition of eutrophication based on the P/B ratio (Smith, 2007). As a temporary alternative, an increase in both production and biomass could be mentioned: "Eutrophication is the increase in carbon production and carbon accumulation in an aquatic ecosystem" (modified from Nixon, 1995 and Rabalais, 2004). Finally, the dispersion of definitions in group 1 reflects a lack of clarity on how to express the phenomenon itself: an increase in productivity.

The *environmental* definitions

Even if nutrient pollution is "only part of the story" (Nixon, 2009), eutrophication has become a research issue mainly due to human activities and their effects on ecosystems. Already the oldest definition collected in this study, Hasler (1947), was dedicated to pollution by nutrients, which is more than 90% of the definitions collected. The term *cultural eutrophication* found in several definitions (e.g., Sathananthan, 2016; Steele, 1974), like other terms such as *artificial*, *manmade*, and *anthropogenic*, focuses the definition on nutrient pollution. The expression "nutrient pollution" is used by the US Environmental Protection Agency website (EPA) at https://www.epa.gov/nutrientpollution/issue, the European Environment Agency (EEA), and the National Oceanic and Atmospheric Administration website (NOAA) at https://oceanservice.noaa.gov/facts/nutpollution.html, in communications on eutrophication. The Web of Science has referenced 144 articles with "Nutrient pollution" in their title, 45% of them dating from the last 5 years. They apply to most of the documents in groups 2 and 3, as well as to a large part of those from group 1. Finally, for many studies related to eutrophication, it might be more relevant to work on a common description of the effects of nutrient pollution than to resort to a new definition of eutrophication.

Ecosystems are known to be complex dynamic systems composed of many components and interrelations, which gives them emergent properties and makes them unpredictable (Jørgensen & Müller, 2000). Moss (2010) inventoried 100 variables to characterize a lake, in the end showing that each lake is unique. This finding can no doubt be applied to other types of ecosystems. Ecosystem responses are also complex. Regressions between nutrient concentrations and ecological quality ratios (EQR) based on phytoplankton and macrophyte communities for five major ecoregions of Europe and major lake types showed that relationships were in general stronger for phosphorus than for nitrogen, and for phytoplankton than for macrophytes (Poikane et al., 2022). Yet specific lake types, especially understudied shallow lakes in the Eastern Continental region may behave differently, often linked to fish-stocking practices (Poikane et al., 2022). We may therefore expect an infinity of ecosystem responses to nutrient pollution. This is what Cloern (2001) meant by "myriad of biogeochemical and biological responses" (group 1). Other scientific definitions mention indirect effects on ecosystems through general expressions like "undesirable changes in ecosystems" (Rabalais, 2010). Group 2 includes multiple definitions that provide details on the primary producer type and add indirect effects. This group can be described as *environmental* in the sense that, compared to the other groups, the content of most of its definitions is exclusively focused on the health (or good functioning) of the ecosystems. However, the diversity of primary producers (Table 5) and indirect effects (Table 6) cited in definitions results in the strong dispersion of definitions in group 2. Despite this lack of genericness, group 2 contains definitions intended to communicate the dangers of nutrient pollution to as many people as possible. The introduction of direct and indirect effects on ecosystems in the definition makes it possible to link visual observations, such as algal blooms and fish mortality, to eutrophication. The definition of Carpenter (2005), which fits the definition of pollution (presence of substances and heat in environmental media—air, water, land—whose nature, location or quantity produces undesirable environmental effects), offers this approach, different from the definitions of group 1, by citing the most emblematic manifestations in freshwaters (algal blooms and anoxia). The deduced definition of the most frequently used words of those collected is clearly linked to group 2. It therefore appears that the eutrophication dealt with in the documents is mainly a matter of nutrient pollution and environmental concerns. Focusing on nutrient pollution and its consequences, group 2 definitions contain those that aim at a wider audience than the scientific community and are written in a pedagogical way (Art, 1993; Bricker et al., 2008; Justić, Rabalais, Turner & Dortch, 1995), sometimes in an encyclopedic way (Díaz et al., 2010; Sathananthan, 2016). Here, the question arises of how we can communicate to the general public the urgency and seriousness of nutrient pollution. The definitions of several dictionaries are found in group 2, but they present differences that still reflect the difficulty of being consensual on the essentials to select on pollution by nutrients. The process of simplification for a pedagogical purpose can produce shortcuts as in the definition of the Cambridge Dictionary, where it can be understood that the growth of plants consumes oxygen (Cambridge Dictionary, 2019). Agreeing on a definition of the effects of nutrient pollution would enable effective communication on eutrophication. However, work remains to adapt and determine the level of detail of such an environmental definition between the very succinct one of Carpenter (2005) and that of Art (1993), which describes a series of processes leading to anoxia.

The *operational* definitions

Like group 2, the barycenter of group 3 is positioned to the right of axis 1 (Figure 6) because its definitions cite both direct and indirect effects. Group 3 contains definitions citing especially the primary producers most commonly associated with water degradation (algae, cyanobacteria, Figure 5i,j). The definitions in this group differ from those in group 2 (barycenter above axis 2) because they also contain terms related to water quality and ecosystem services. Cloern et al. (2013) introduced the notion of water degradation, which can be classified into group 3. The definitions of group 3 can be called *operational* because they tend to provide a framework for actions aimed at the protection and restoration of ecosystems.

The direct and indirect effects of eutrophication became increasingly visible and harmful during the 20th century, which led to degraded ecosystem services, starting with the supply of drinking water. There was a need to define the contours of a common framework in order to assist managers faced with this problem in making decisions and implementing mitigation measures. From the 1970s onwards, the Clean Water Act in the United States, the OSPAR Guidelines and the Water Framework Directive (WFD) in Europe have supported ample research to describe and manage the problems caused by anthropogenic eutrophication. Andersen et al. (2006) found that, within a monitoring and management context, Nixon's definition was difficult to apply and that there was no consensus definition of eutrophication. They therefore targeted the enrichment of water by nitrogen and phosphorus by considering indirect effects on ecological integrity and ecosystem services. Again, for the WFD, Ferreira et al. (2011) argued that the scientific definition of Nixon (1995) left too much room for interpretation from a judicial perspective and gave another definition with similar descriptors to those of Andersen et al. (2006). In fact, Andersen et al. (2006) and Ferreira et al. (2011) did not seek to define eutrophication but pollution by nitrogen and phosphorus. From a judicial point of view, again it would be simpler to treat nitrogen and phosphorus as pollutants without relying on eutrophication. But in this way, concentration thresholds must be defined. Because thresholds are set for biological effects, the problem comes back to the consequences and effects of these substances. That is a problem that regulations such as the WFD have to face.

CONCLUSION

The multiplicity of definitions of eutrophication in the literature shows that we are not yet able to define it accurately. The problem comes first from the definition of words that can be used to characterize the process like "production" and "productivity." More fundamentally, the eutrophication process is closely linked to the very functioning of ecosystems, knowing that each of them has its own structure, itself governed by a set of internal pressures and interactions, being dynamic complex systems. The scientific definition of eutrophication, which will always depend on our level of knowledge of the functioning of ecosystems, is proving to be a long-term project.

Although still to be better defined, the word eutrophication is widely used in work related to anthropogenic nutrient pollution, while the word "pollution" is well defined. The many scientific disciplines involved in this topic, ranging from functional ecology to water treatment, have generated a large number of definitions that have often been adapted to the subject of the work. In addition, nutrient pollution is a high-stakes topic that managers of aquatic ecosystems must address. The need for legislation and action has led to new definitions of eutrophication, but these are clearly linked to nutrient pollution. An important issue is also to formalize the effects of nutrient pollution in an educational way, and dictionary definitions would benefit from being more unified. With this objective, focus communication on the term "nutrient pollution" rather than "eutrophication" would clarify the societal issue independently of the scientific question devoted to properly defining the eutrophication process itself.

AUTHOR CONTRIBUTIONS

Conceptualization and draft preparation: Alexandrine Pannard, Philippe Souchu and Elisabeth M. Gross. *Data collection and statistical analysis*: Alexandrine Pannard and Philippe Souchu. *Support for bibliographic tools*: Monique Delabuis. *Writing*: Alexandrine Pannard, Philippe Souchu, Christian Chauvin and Elisabeth M. Gross. *Review and editing*: Alexandrine Pannard, Philippe Souchu, Elisabeth M. Gross, Erik Jeppesen, Nancy N. Rabalais, Chantal Gascuel-Odoux, Christian Chauvin, Alain Ménesguen, and Yves Souchon. *Management and supervision of the expertise in which this study is included*: Gilles Pinay, Chantal Gascuel-Odoux, Yves Souchon, Alain Ménesguen and Morgane Le Moal. All authors have read and approved the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

We produced derived data from already published and publicly available definitions of eutrophication. The 138 collected definitions (Pannard, 2024a) are available in Figshare at https://doi.org/10.6084/m9.figshare.24004110. The derived data coming from the content analysis of the definitions are available in Figshare in an XLSX file (Pannard, 2024b) at https://doi.org/10.6084/m9.figshare.24004113 and a CSV file (Pannard, 2024c) at https://doi.org/10.6084/m9.figshare.24004116. The Rscript used in RStudio for the MCA statistical analysis (Pannard, 2024d) is available in Figshare at https://doi.org/10.6084/m9.figshare.24004119.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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