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Systematic Review

Mapping Topic Evolution across the 40-Year-Old Long-Term Ecological Research MareChiara Site in the Gulf of Naples, Italy

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Abstract: The forty-year-old Long-Term Ecological Research MareChiara (LTER-MC) program started on 26 January 1984, with fortnightly oceanographic sampling until 1991 and then, from 1995, with weekly sampling up to the present time. LTER-MC produced >150 publications that have been cited by thousands of other studies. In this scoping review, we analyzed this corpus using a semantic approach based on topic modeling, a machine-driven procedure to identify and map topics and their interactions. Understanding the causes behind the evolution of scientific topics, their emergence, splitting, hybridization, or merging within a scientific community is an important step in science policy in managing collaborative research and bringing it into the future. Across different topics, mainly represented by studies on Natural History, Biodiversity, Phenology, Life Cycles, and Community Ecology, the LTER-MC work expanded the knowledge on planktonic organisms, describing in detail their lifestyles and delineating their relationships with environmental conditions. In presenting these results, the potential strengths, weaknesses, opportunities, and threats connected to the overall scientific dimension of LTER-MC are discussed. Finally, the upcoming effort is envisioned in reinforcing internal collaboration to integrate basic and applied research around scientific investigations suitable for establishing a stronger interaction between science and policy, as indicated by the United Nations Decade of Ocean Science for Sustainable Development.

Keywords: Long-Term Ecological Research; marine ecosystems; marine observatories; plankton; topic evolution

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1. Introduction

Long-term ecological research (LTER) focuses on understanding ecosystem dynamics by monitoring environmental variables, biodiversity, and ecological processes over decades [1]. Such research aims at understanding how different natural systems, both terrestrial and aquatic, respond to environmental change and human impacts [2,3], and allows the forecasting of future environmental trajectories [4]. This effort enables the scientific community to provide human society with crucial data for informing policy making that drives habitat conservation and restoration [5] and environmental management in general [6]. In such a global context, the International LTER network (ILTER) [7] facilitates the collaboration, data sharing, and research coordination among 747 LTER observational sites, covering all biomes on Earth, such as the marine realm, represented by 48 sites, including LTER MareChiara (LTER-MC; Gulf of Naples; Italy; Central Mediterranean Sea, Lat 40°48.5′ N, Long 14°15′ E) managed by the Stazione Zoologica Anton Dohrn (Figure 1).

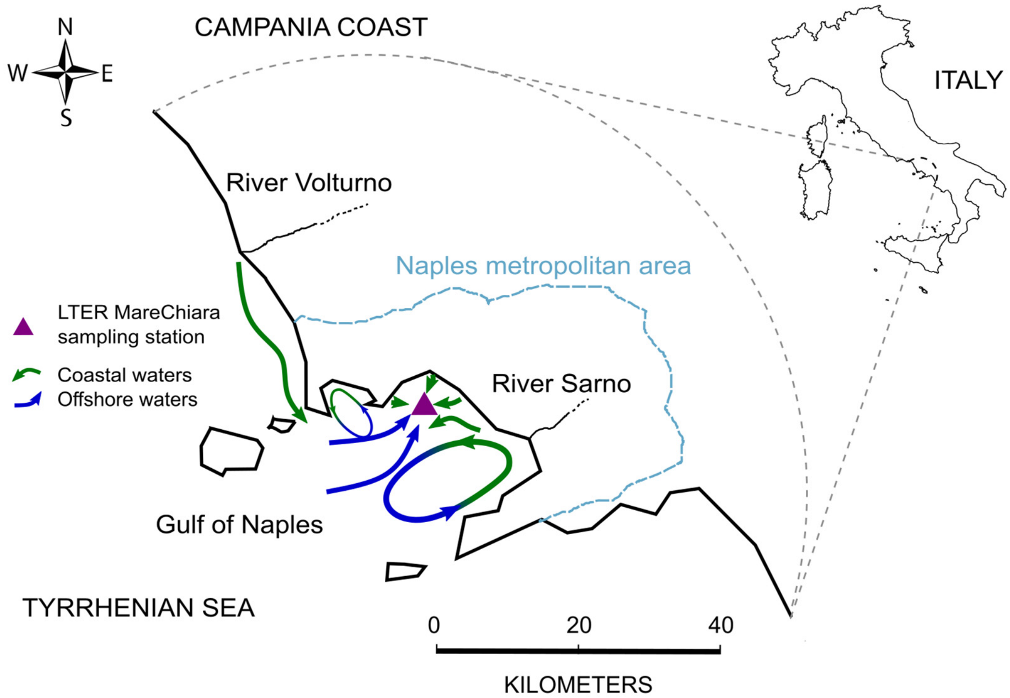

Figure 1. A map of the Gulf of Naples (Central Mediterranean Sea, Italy) and the main sampling station of the Long-Term Ecological Research MareChiara site.

The forty-year-old LTER-MC research site started in 1984, on 26 January, with fortnightly oceanographic sampling until 1991 and, from 1995, weekly sampling [8] up to the present time (https://deims.org/0b87459a-da3c-45af-a3e1-cb1508519411, last time accessed on 9 August 2024). Taking as a reference a sampling station two miles away from the coastline, where the sea bottom sits at 75 m below the sea surface, LTER-MC has been monitoring the physical and chemical conditions of the water column and the diversity of plankton therein (Figure 2), studying the dynamics of the shelf ecosystem facing the metropolitan area of Naples (~3 M inhabitants). Due to the geomorphological and hydrological conditions of the area, the LTER-MC sampling site intercepts the oceanographic front between coastal and offshore waters, which alternate at short time scales [9], thus providing an important case study for multifaceted plankton research [10], including process-based investigations on plankton dynamics in the face of environmental shifts [11].

Over the past forty years, the LTER-MC research program has produced >150 publications that have been cited by thousands of other studies worldwide (average citations per article = 59.5). This literature corpus expanded the knowledge on elusive planktonic organisms, describing in detail their lifestyles and delineating their many relationships with environmental conditions, such as the constantly rising sea temperature and the freshwater discharge from urban areas [12]. Such an effort has ensured the availability of background knowledge, data resources, and observational capacity for several research projects and marine policy initiatives. The success of LTER-MC stems from the human capital built up over time through the ingenuity and dedication of dozens of scientists who, supported by tens of university and Ph.D. students from all over the world, have contributed to the birth, growth, and survival of this research to date, following a community behavior common in LTER research [13].

This paper aims to analyze the literature corpus produced by the LTER-MC community and to map the main scientific topics and their evolution over the past forty years. Understanding the causes behind the temporal dynamics of scientific topics in terms of their emergence, splitting, cross-fertilization, or merging within a scientific community represents an important step in science policy, e.g., to manage collaborative research and to bring it into the future [14,15]. For instance, the birth of emergent topics is more probable in conceptually fragmented communities when mutually segregated research areas establish new connections [16,17]. As only 10% of highly cited topics in science and technology belong to emergent topics [18], citation analysis indicates that, to achieve a long-lasting scientific impact, investigations should give preference to works that bridge topical domains over those that pursue intra-domain recognition, i.e., increase the consensus (and citations) around a single topic [19].

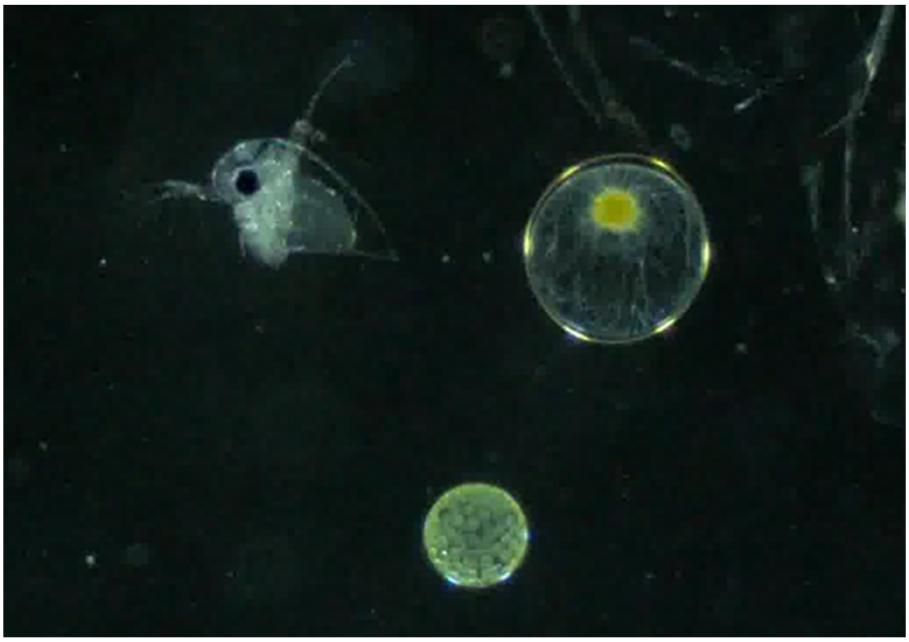

Figure 2. Planktonic organisms from the Gulf of Naples collected during a sampling at the Long-Term Ecological Research MareChiara site. Photograph by Domenico D'Alelio, with the instrumentation provided by the Marine Organism Taxonomy (MOTax) unit of Stazione Zoologica Anton Dohrn in Naples (Italy). The maximum dimension of the organisms in the picture is ~0.5 mm.

In pursuing this paper's aim, a scoping review of the LTER-MC literature was carried out using a semantic approach based on topic modeling, a machine-driven procedure to identify and map topics and their interactions in a literature corpus [20]. In this type of analysis, topic evolution is tracked over time, identifying conceptual intersections and missing links, plus potential knowledge gaps. In presenting the results, strengths, weaknesses, opportunities, and threats connected to the overall scientific dimension of the LTER-MC research are detailed, and implementation actions for the upcoming decades are envisioned, considering the need for a better integration between science and society in accordance with the United Nations Decade of Ocean Science for Sustainable Development [21].

2. Materials and Methods

2.1. LTER-MC Publication Dataset

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [22] scheme was followed during the analyses (see PRISMA flow diagram in Figure 3). In particular, the PRISMA Extension for Scoping Reviews (PRISMA-ScR) checklist [23] was used to guide the conduct of this review (Supplementary Materials S1).

A publication dataset was built that included studies published by the LTER-MC community from 1984 to 2023 (n = 160), i.e., those peer-reviewed scientific articles showing a specific reference to the long-term station MareChiara (Figure 1) and being retrievable on public databases, such as Web of Science, Scopus, and Google scholar. A review was carried out on this dataset by primarily analyzing the flow of information in terms of word sharing among the titles and abstracts of all the papers, following the rationale described in previous studies [24]. In this way, it was possible to exclude biases in the construction of information-flow networks potentially introduced by the sharing of words that were neither strictly scientific nor the focus of the studies.

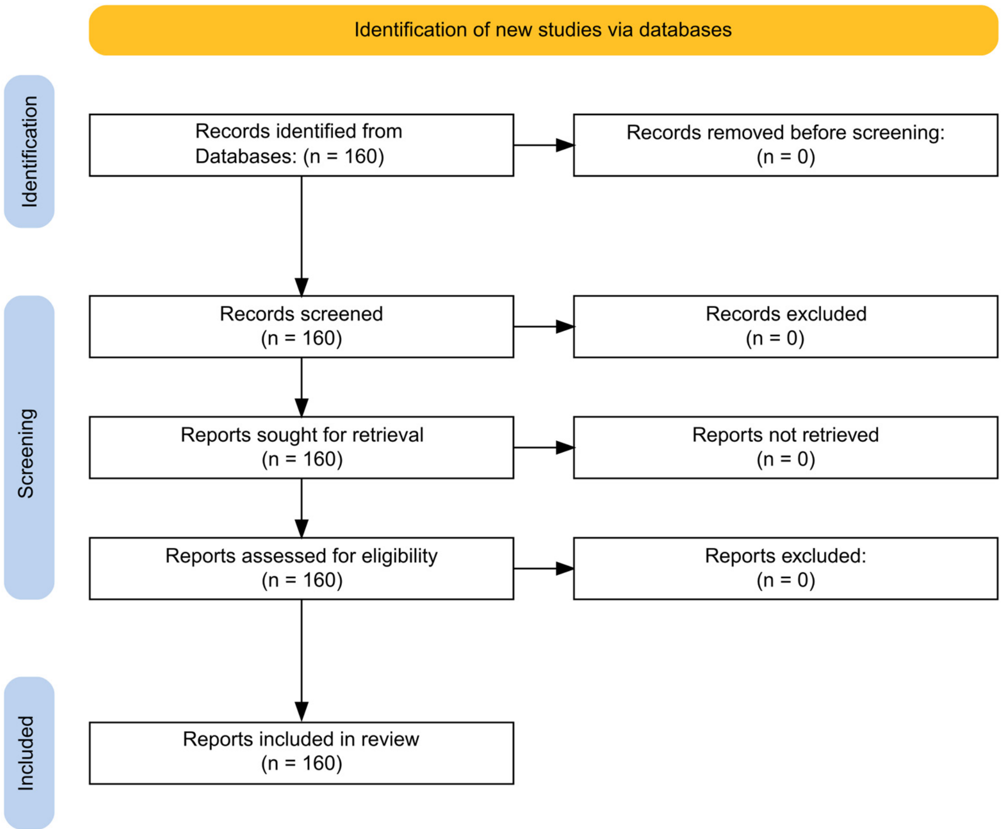

Figure 3. PRISMA flow diagram showing the screening of the identified records for the scoping review.

2.2. Topic Analysis

The publication dataset was imported into R version 4.3.2 (https://www.R-project.org/, last time accessed on 4 May 2024), where papers' titles and abstracts were joined as one, and a single column was then used in topic modeling [20] using the textmineR package [25]. Using the papers' titles and abstracts, a document-term matrix (DTM) was produced that included single terms and bigrams (i.e., sequences of two terms) that had been previously lemmatized (in computational linguistics, lemmatization is the process of grouping together different inflected forms of the same word, e.g., *change* and *changing* are converted into *chang*). The DTM was screened to remove words not referring to scientific fields (e.g., Naples, MareChiara). Finally, for the entire DTM, it was possible to estimate the term frequencies, i.e., the number of times the term or bigram appeared in the document-term matrix, and the document's frequency, i.e., the number of documents in which a term or a bigram was included.

Using the FitLdaModel function of the textmineR package, Latent Dirichlet Allocation (LDA) topic modeling, a probabilistic approach to identify topics as groups of words that co-occur together more frequently than expected by chance alone, was employed [26]. The number of topics must be defined a priori to fit the topic model. However, as there are no standardized methods for choosing the number of topics to use in the analyses, it was decided to apply ten repetitions of the [5:20] LDA topic range and the number of topics that maximized overall coherence. Probabilistic coherence (i.e., how associated words are in a topic) was measured using the CalcProbCoherence function of the textmineR package. Then, the inter-topic distance was calculated using the Hellinger metrics, i.e., by the CalcHellingerDist function, and topics were analyzed by hierarchical clustering (Ward's method) using the hclust function with the ward.D option.

2.3. Network Visualization and Statistical Analysis

Connections between the five top terms and the main topics were visualized with an alluvial diagram using the alluvial function (https://github.com/mbojan/alluvial, last time accessed on 4 May 2024). Yearly trends of papers and the most probable topic they belong to were displayed using a bar graph. Moreover, temporal dynamics of the publications were analyzed using functions of the wql R package [27]; measuring the change in trends over the time of the publications was performed through the Mann–Kendall test using the function mannKen, while the presence of change points within the time series was tested by applying the non-parametric Pettitt test using the pett function [27].

The conceptual intersection among topics was explored by deriving two information-flow networks from the LTER-MC publication dataset. The first was a word network resulting from the VOSviewer software analysis (version 1.6.20) [28], which displayed the most relevant co-occurring words in the LTER-MC literature. The second semantic network, a paper network, was based on a matrix of conceptual distance among papers derived using the Hellinger distance, estimated using terms shared by papers' titles and abstracts. The distance was converted into a similarity matrix (retaining values > 0.6), and this latter was used to build an undirected network representing conceptual intersections among papers. The network was visualized and analyzed with Gephi version 0.10.1 [29]; the network modularity, i.e., the presence of distinct groups of network nodes that are strongly connected, was identified using the Louvain algorithm [30]; and the papers' betweenness centrality, i.e., the proportion of times a network node acts as a bridge along the shortest path between two nodes, was estimated [31].

3. Results and Discussion

3.1. Mapping Topics in the 40-Year-Old LTER MareChiara

A total of 160 papers published between 1984 and 2023 comprised the LTER-MC literature corpus analyzed herein (Supplementary Table S1). Therein, the most frequent terms were ″diatom″ and ″pseudo_nitzschia″, which were dominant in the whole DTM (Tables 1 and 2). Diatom occurred in 42% (n = 67) of LTER-MC papers, and it was also more highly represented than ″plankton″ overall, while ″diver″ (lemma for diversity) occurred in 36% (n = 57) of the documents. Among bigrams, ″pseudo_nitzschia″, which referred to the planktonic diatom genus *Pseudo-nitzschia*, occurred in 23% (n = 37) of the papers, i.e., about twofold more frequently than all other bigrams. The related bigram ″nitzschia_multistriata″, referring to *Pseudo-nitzschia multistriata*, and ″life_cycle″ occurred in 13% (n = 21) of the papers. This indicates that studies dealing with diatoms (photosynthetic eukaryotic unicellular organisms, i.e., protists or eukaryotic phytoplankton), including key genera, their diversity and life cycles, were main topics in the LTER-MC scientific production, in line with previous assessments [10].

Planktonic diatoms, which are hugely diverse [32] and drive biogeochemical processes [33], are the main primary producers in coastal systems, contributing to around 20% of the primary production at the global level, and they provide multiple ecosystem services, such as boosting the delivery of organic matter to higher trophic levels, including commercially exploitable marine organisms [34]. Based on LTER research, diatom population dynamics over the long term have been deeply investigated worldwide, and these organisms have been reported among the dominant phytoplankton groups in different Mediterranean regions, such as the Western sector [35] and the Adriatic Sea [36].

In this context, two complementary conditions may have facilitated the rise of LTER-MC papers focusing on diatoms and, in particular, the toxigenic genus *Pseudo-nitzschia*. Firstly, diatoms are easy to cultivate and study with several approaches, from cytology to molecular biology [37]. Secondly, some of the diatom genera have socio-economic relevance; for instance, *Pseudo-nitzschia* species frequently occur in the Mediterranean Sea [38], and their blooms may impact coastal economies [39]. Therefore, biological studies employing in vitro approaches are more reliable on photosynthetic protists like *Pseudo-nitzschia*, and such studies are highly desirable to understand the mechanisms regulating diatom proliferation, which is driven by many biological factors, such as life-cycle shifts [40].

Table 1. Frequency of the top terms (lemmatized words) in the analyzed dataset. TF stands for term frequency, and it is the number of times a term appears in the document-term matrix; DF stands for document frequency and represents the number of documents that include a term.

Term (Lemmatized Word)	TF	DF
diatom	191	68
plankton	149	64
cell	133	45
divers	130	58
pseudo	114	40
phytoplankton	108	45
nitzschia	107	38
pseudo-nitzschia	107	38
abund	103	50
sequenc	84	38

Table 2. Frequency of the top bigrams (terms composed of two lemmatized words) in the analyzed dataset. TF stands for term frequency, and it is the number of times a bigram appears in the document-term matrix; DF stands for document frequency and represents the number of documents that include a bigram.

Bigram (Lemmatized Words)	TF	DF
pseudo_nitzschia	107	38
food_web	39	11
life_cycl	34	21
nitzschia_multistriata	32	21
plankton_diatom	30	22
sexual_reproduct	30	14
diatom_pseudo	29	21
cell_size	15	10
diatom_genu	15	11
genu_pseudo	15	11

It appears evident that, in sitting at the boundary between basic and applied science, diatom research has attracted myriads of scientists worldwide, conspicuous funds, and research capacity: this condition has plausibly paved the way to the success of diatom-focused studies in the LTER-MC program. Based on traditional counting methods, diatoms appear as the most abundant photoautotrophic unicellular organisms living among coastal plankton, including that of the Gulf of Naples, because they perform better than other phytoplankton at higher nutrient conditions [41]. However, innovative detection methods, like the analysis of the environmental DNA, indicate that most of the unicellular diversity in plankton is associated with non-diatom groups, even in the Gulf of Naples [42]. These features suggest an under-estimation (and investigation) of other important planktonic (not exclusively photosynthetic) protists, whose relevance in the Gulf of Naples was probably weakly perceived.

Despite the quantitative dominance of diatom papers, based on semantic analysis carried out on multiple combinations of terms and bigrams occurring in the DTM, the LTER-MC literature was found to comprise eight main topics (Table 3; Figure 4A).

The similarity among these topics leads to the formation of two topical clusters: a first cluster made up of topics 1, 3, 4, 7, and 8 and including 97 papers mostly related to phytoplankton; and a second cluster, made up of topics 2, 5, and 6, that included 63 more generalist papers. Based on the prevalence and coherence values, semantic similarity clustering, and expert knowledge, we aggregated the eight machine-derived topics into five (Figure 4B–D; Supplementary Table S1), denominated as: Biodiversity (topics 1 + 8), Natural History (topics 3 + 4), and Life Cycles (topic 7), sitting in cluster I; and Phenology (topics 2 + 5) and Community Ecology (topic 6), sitting in cluster II. These topics are in good agreement with those indicated by a previous LTER-MC review [10].

Table 3. Semantics and main characteristics of the topics identified from topic model analysis. Prevalence is the probability of the topic's distribution in all the documents. Coherence is a measure of the quality of a model topic from the point of view of human interpretability based on how associated words are in a topic.

Topic	Prevalence	Coherence	Top Five Terms/Bigrams (Lemmatized Words)
1	12.1	0.44	sequenc, sampl, genu, cyst, stage
2	13.5	3.15	abund, copepod, zooplankton, mc, environment
3	11.7	2.19	cell, morpholog, light, genet, cryptic
4	12.7	0.06	cycl, size, reproduct, type, investing
5	13.4	0.37	phytoplankton, popul, rate, lter, product
6	12.6	3.45	plankton, commun, web, trophic, food
7	12.3	0.42	diatom, pseudo, nitzschia, pseudo_nitzschia, sexual
8	11.7	0.05	divers, diatom, taxa, region, winter

Biodiversity is the richest aggregated topic (41 papers) (Figure 4A). Most Biodiversity papers (37) deal with the exploration of phytoplankton diversity in the study area (see, e.g., [43,44]); some of these papers are at the edge of the ecological domain (see, e.g., [45–47]), even though they are limited to unicellular organisms. Overall, the Biodiversity group shows a dominance of taxonomical and molecular investigations on diatoms at the genus and species level (see, e.g., [48,49]), while fewer studies deal with other phytoplankton groups (see, e.g., [50–52]) and zooplankton [53,54], many of which explored biodiversity through environmental DNA analysis. At LTER-MC, Biodiversity was studied across seasons, for instance, revealing that an apparently poor period like "winter" (see the top five Biodiversity terms in Figure 4C) was instead rich in distinctive species assemblages of both diatoms [45] and other planktonic protists, like dinoflagellates [47]; Biodiversity was also described below the species level by reporting the occurrence of different life-cycle "stages" (see Figure 4C) of the same species [50]. Finally, most Biodiversity studies focused on organisms from the Gulf of Naples in comparison with other, mainly Mediterranean, sites (e.g., [55]).

Phenology (37 papers) is the study of the natural processes with seasonal periodicity, like the reproductive cycle. In the LTER-MC literature corpus, the topic Phenology is semantically distant from Biodiversity, Natural History, and Life Cycles (Figure 4A). This result may be peculiar (as phenology is studied by reiterated biodiversity observations), but it stems from a thematic divide: while cluster I topics are mainly phytoplankton-related, Phenology is richer in zooplankton-focused studies (19 papers) dominated by copepods (i.e., planktonic crustaceans; see e.g., [56–58]), and poorer in papers about planktonic protists (n = 9; e.g., [59,60]). The dominance of zooplankton studies in the Phenology topic appears to be driven by cultural factors, as the population dynamics of zooplankton species (more easily identifiable than unicellular ones) historically represents a primary topic in biological oceanography [61], mainly because of the relevant role of zooplankton for both biological oceanographers and fishery scientists [62]. Among zooplankton, copepods attract more scientific interest because these crustaceans are the most abundant zooplanktonic organisms (e.g., [63,64]) and are key players in marine food webs [65]. Finally, it is worth noting that Phenology at LTER-MC also includes studies on seasonal changes in water-column physics (e.g., [66,67]) and others about observational approaches to better describe sea periodicities (e.g., [68]). One must also notice that the sub-topic Long-Term Monitoring has higher visibility in Phenology than in other LTER-MC topics (see, e.g., [69]).

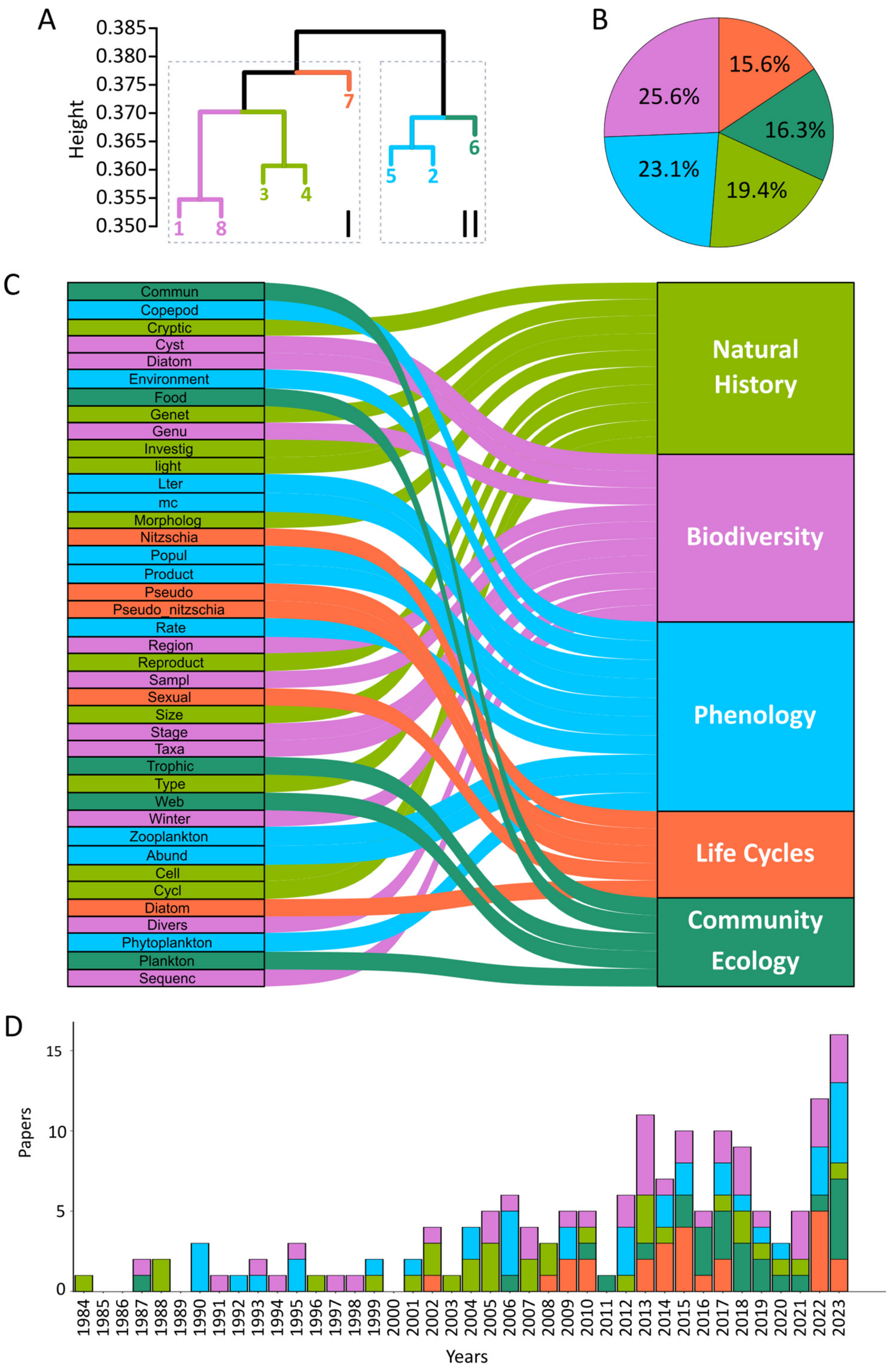

Figure 4. Topic modeling results from semantic analyses of the LTER-MC literature dataset. (**A**) Cluster analysis (hierarchical clustering, Ward's method) of topics based on the LTER-MC document-term matrix; color coding indicates the aggregation of topics, which are, in turn, grouped into main clusters (I and II). (**B**) Proportion of LTER-MC papers associated with the five aggregated topics. (**C**) Alluvial diagram mapping connections among the top five terms of the LTER_MC DTM and the aggregated topics resulting from topic modeling. (**D**) Temporal dynamics of the publication of papers associated with the five main LTER-MC topics. Panels in (**A**–**D**) follow the same color coding. Numbers 1-8 in panel A refer to the topics indicated in Table 3.

Natural History (31 papers) deals with observational and descriptive studies of plankton in their environment (Figure 4A). This topic includes the oldest LTER-MC paper [70]. Studies on phytoplankton and diatoms are dominant herein (24 papers), from the description of natural phenomena like blooms (e.g., [70,71]) to seminal observations of biological processes explained more by interpretation than experimentation (e.g., [72]), which, in turn, gave rise to other topics, like the fine-scale exploration of Biodiversity (e.g., [73]) and Life Cycles (e.g., [74]), especially in diatoms. Moreover, behavioral studies are an important component of Natural History, such as diatom life strategies in coping with light [75], the feeding habit of planktonic dinoflagellates (i.e., not strictly photosynthetic protists) [76], the swimming performance of copepods (i.e., planktonic animals) [77], and the predatory behavior of non-photosynthetic protists [78].

Life Cycles (25 papers) is the smallest topic in topical cluster I and overall; this topic is set apart from Biodiversity and Natural History, but it is closer to these than to other topics (Figure 4A). The totality of Life Cycles papers is dedicated to studies on diatoms, and most of them appear to have been incepted by previous research belonging to Natural History. Life Cycles papers include the investigation, based on in-situ observations, of diatom demography and sexual reproduction (e.g., [79,80]), the temporal and spatial distribution of species and varieties (e.g., [81,82]), and genetic patterns in relation to reproduction dynamics (e.g., [83]), with a neat dominance of studies relating to the diatom genus *Pseudo-nitzschia*. Within the Life Cycles topic, *Pseudo-nitzschia* is also a key organism for functional studies to investigate mechanisms regulating sex in these diatoms (e.g., [84]).

In the LTER-MC literature corpus, close to Phenology is the Community Ecology topic (26 papers), represented by 12 papers about biotic interactions across all plankton groups (i.e., both protists and metazoans) (Figure 4A). Studies span from trophic to non-trophic interactions (e.g., [85]), and some of them investigate planktonic food webs with stable isotopes (e.g., [86]), environmental DNA analysis [87], and field-data-derived models (e.g., [11]). Six Community Ecology papers discuss the spatial and temporal variability of phytoplankton communities (e.g., [9,88]), also employing innovative, non-optical, methods (e.g., [42,89]), and one paper deals exclusively with zooplankton [90]. Most Community Ecology papers are related to ecosystem services and societal issues (see, e.g., [91]), and four papers discussing the socio-ecological value of LTERs (e.g., [92]) fall into Community Ecology based on a higher conceptual affinity with this topic.

3.2. Topic Evolution in LTER MareChiara

The origin of LTER-MC topics is retrievable from the publication dynamics (statistically significant increase of 0.2 articles per year, p-value < 0.001) across its forty-year lifespan (1984–2023) (Figure 4D). Four out of five topics detected by the analysis presented herein emerged in papers during the first years of the time series (1984–1990), except for Life Cycles, which only appeared in 2002. Natural History is the oldest topic, appearing with the birth of LTER-MC (1984), while Biodiversity emerged slightly later (1987), and Phenology years later, with papers reporting the first time-series data (1990). Community Ecology is among the four oldest topics (appearing in 1987), but it was the least-represented topic until the first twenty years of the time series. The dynamics of LTER-MC topics suggest that observational/natural history studies provided the primary background for the later interest into more detailed investigations on specific organisms about their diversity (how many species are there?) and phenology (when and why they occur?). Other topics came later, like thematic propagules well rooted in the previous background knowledge.

The LTER-MC scientific production underwent two reliable phases, with a statistically significant (p-value < 0.001) change point between 2003 and 2004: it accounted for <1 paper year^{-1} in the first two decades (28 papers) and was much more prolific after 2003 (132 papers), with peaks of >10 and >15 paper year^{-1} in 2013 and 2023. This finding suggests that the scientific productivity of this time series is positively related with its persistence in time (similarly to other LTERs, [93]), even though such a persistence does not necessarily favor the emergence of new topics. Overall, the scientific productivity was not univocally positively related to the emergence of new topics like Life Cycles, but it appeared to be driven by the apparent maturity of the older topics, like Biodiversity, Phenology, and Community Ecology. This latter became more relevant only in the 2010s but played an important role in enhancing scientific productivity. Eventually, despite representing a key topic in the 2000s and the first half of the 2010s, productivity in Natural History underwent a remarkable decline in the last decade.

Topic evolution in a disciplinary field is a convoluted process driven by different factors, such as the cultural identity of scientists and topic attractiveness [17–19]. On the one hand, the first factor mentioned above is well represented by the distribution of different topics among LTER-MC papers, dominated by studies produced by experts of phytoplankton perceiving the primary importance of investigating the diversity and life cycles of key organisms like diatoms. On the other hand, the number of citations of papers associated with a topic can reflect the general interest around that topic, attracting even more attention by scientists at the local level. In the LTER-MC literature corpus, even though Biodiversity showed overall the highest citation record (yearly normalized citations = 163), all topics were attractive—Phenology, Natural History, and Community Ecology accounted for 134, 140, and 154 yearly normalized citations, respectively, while Life Cycles' papers showed the lowest citation record (90 yearly normalized citations), but it represented the smallest group of papers.

Thus, Natural History's decline in the LTER-MC literature corpus may stem from causes different from its low scientific attractiveness. One must consider that topics evolve, and their rise and fall in the scientific literature stem from conceptual merging, splitting, hybridization, and segregation [94]. To investigate these dynamics, connections were mapped using semantic networks between concepts expressed in terms of words and between papers associated with different topics in the LTER-MC literature corpus. The main co-occurring words in this corpus display a conceptual network, as shown in Figure 5. Therein, words aggregate or reciprocally segregate based on the uneven distribution of inter-word connections, identifying three modules. In Figure 5, the blue module includes words related to Life Cycles and is strongly connected with the gray module, aggregating words associated with Biodiversity and Natural History topics; the yellow module includes words referring to Phenology and Community Ecology.

The blue module appears to spin off the gray module (Figure 5), indicating that the literature concerning Life Cycles may have emerged from a broader and more taxonomy-based corpus but acquired an individual conceptual dimension thanks to studies on the diatom life cycle and genomics, mainly on the *Pseudo-nitzschia* genus. The word ″size″ is a conceptual bridge between the blue and gray modules, while ″model″ (in the blue module), ″taxon″ (short for taxonomy), and ″ident″(ity) (gray module) connect these latter words with the yellow module. This observation indicates that ecological investigations originated from the taxonomical field and were mainly linked with biodiversity and life history exploration at the species level, even based on modeling investigations. Moreover, the blue–gray modular cluster (dominated by phytoplankton-derived words) is more scattered and apparently broader in scope (in terms of words and inter-word connections) than the yellow one; the latter is more focused on ecological investigations, like changes in plankton (including both phyto- and zooplankton) populations and communities over time and in relation to environmental factors.

The semantic network based on word co-occurrence in the LTER-MC literature corpus was also compared with an analogous network based on similarity among LTER-MC papers (Figure 6). The two analyses gave comparable, though not equal, results: the paper network includes three modules as well, one (white nodes; Figure 6) in which the 76% of the papers deal with topics expressed by words populating the blue–gray phytoplankton module in the word co-occurrence network (Figure 5) and belonging to Natural History, Biodiversity, and Life Cycles topics; the other modules show a lower topical identity, as both included a 50–50 proportion of papers belonging to the topical clusters I and II (as in Figure 4). This observation indicates that, even though a topic can be dominant in a single paper, the latter is not univocally associated with a single topic, but topics can also hybridize through papers. The higher aggregation of cluster I papers in the white module of the network suggests the higher conceptual segregation of the phytoplankton-related papers.

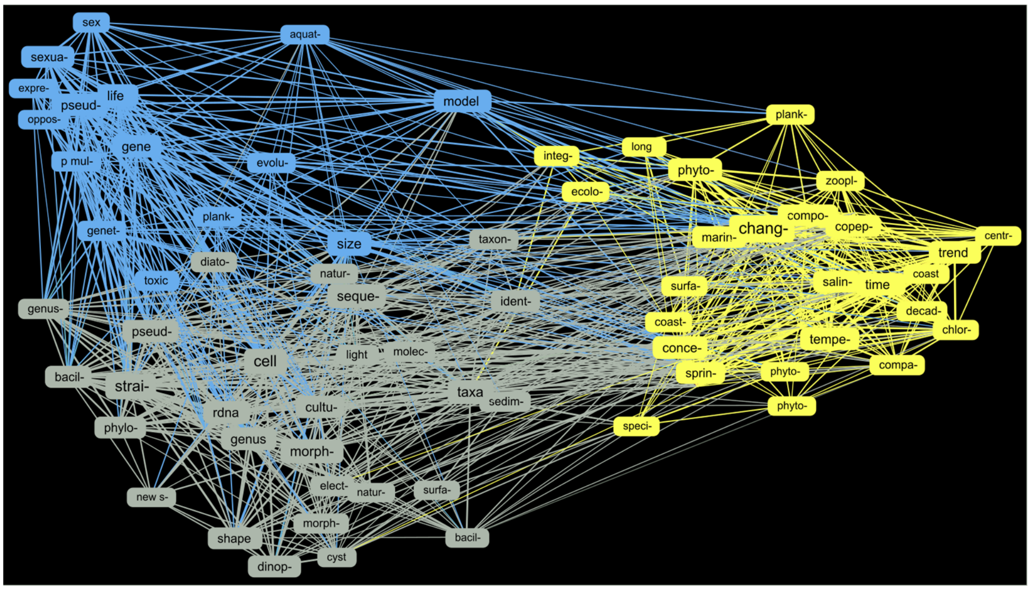

Figure 5. Semantic network resulting from the VOSviewer analysis and displaying the most relevant co-occurring words (lemmatized terms) in the LTER MareChiara literature. Different colors indicate distinct modules, i.e., groups of words co-occurring more frequently. Link weight is proportional to the words' co-occurrence. Intra-modular links have the same color as the module to which they belong. Inter-modular links are of mixed color. Words longer than 5 letters are indicated with a "-" and are explained in Supplementary Table S2.

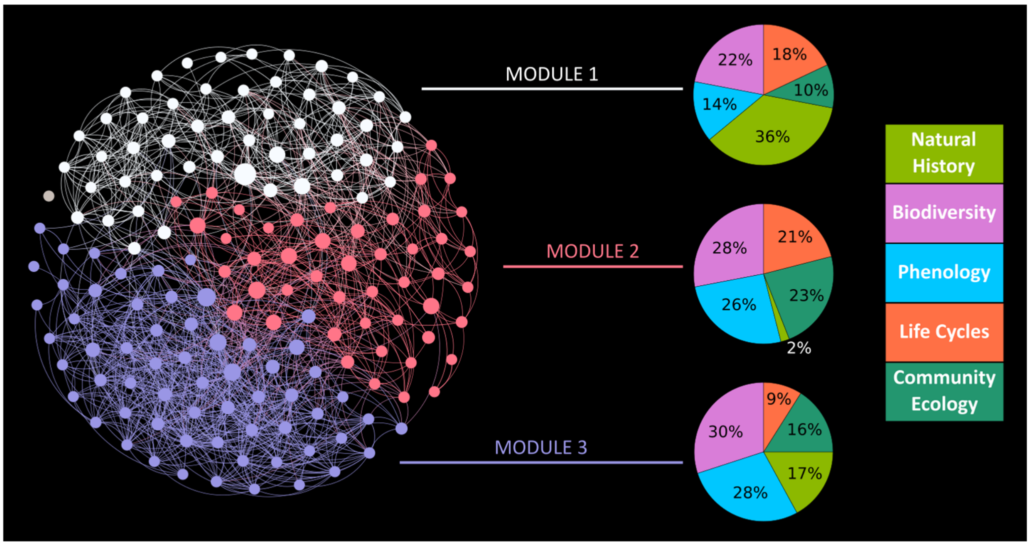

Figure 6. Semantic network based on conceptual similarity among LTER-MC papers (**left**). Each node is a paper; color coding indicates different modules, i.e., groups of papers showing a higher conceptual similarity; node size is proportional to betweenness centrality, i.e., the proportion of times a paper acts as a bridge along the shortest path between two papers. Pies (**center**) indicating the distribution of LTER-MC aggregated topics in the three modules of the paper network (pie colors are the same as in Figure 4); numbers in each pie are the percentages of papers associated with different aggregated topics, which are summarized in the color legend (**right**).

3.3. Strengths, Weaknesses, Opportunities, and Threats in LTER MareChiara

From the semantic analyses of the LTER-MC literature corpus, the authors of the present study derived some considerations about possible strengths, weaknesses, opportunities, and threats connected with the overall scientific dimension of the research program under investigation, which are described in the following paragraphs.

The main strength of LTER-MC appears to be the profound and consolidated knowledge of the biology of plankton, which became traditional in the frame of this multidecadal research through at least three generations of active researchers [10]. The LTER-MC community accumulated experience and capacity in studying plankton biodiversity from different perspectives—from morphological, genetic, and functional points of view [43–54]. At the same time, this community demonstrated a tendency to innovate biodiversity studies by introducing multi-disciplinarity in coastal observations in space and time at the local scale, especially in the third and fourth decades (see, e.g., [9,87,91]), thus allowing the co-existence of several methodological approaches and the acquiring of skills in in situ, in vitro, and in silico analyses, which are all useful for describing planktonic life at different levels of biological complexity from the cell to community levels [95]. Multi-disciplinarity allowed for the investigation at high detail of fine-scale biological processes, such as reproductive cycles and the behavior of key planktonic organisms in their environment or semi-controlled conditions [79–84]. Such achievements also contributed to the recent establishing of the "augmented" observatory, NEREA, in the Gulf of Naples, involving the same LTER-MC community and focusing more deeply on omics technologies (https://www.nerea-observatory.org/, last time accessed on 9 August 2024).

The main weakness of LTER-MC may be its thematic polarization, represented primarily by the inflation of studies about (mainly eukaryotic) phytoplankton, mainly in the Biodiversity topic. Phenology and long-term trends appear as under-investigated in phytoplankton, but they represent a primary topic in studies about zooplankton (mainly about animals with body size = 200–20.000 μm) (e.g., [56–58]). Studies about diatoms and copepods (Figure 7) are predominant in the LTER-MC literature corpus, reducing the room for studies about other planktonic organisms playing not-negligible roles in plankton communities, and therefore in marine ecosystems, such as prokaryotic plankters (e.g., [96]), heterotrophic and facultative photosynthetic protists [97], and jellyfish [98]. Consequently, the integration of the information available, such as phyto- and zooplankton data, or biological data with physical–chemical data, should be improved. Finally, natural history, observational, descriptive, and curiosity-driven studies are becoming less popular, and this may become detrimental for ecological studies [99].

In the present scientific context, the empowering of the LTER-MC community, and therefore research, cannot exclude exploiting all the opportunities provided by the UN Ocean Decade [21] and its challenges [100] toward a scientific reaction to the most pressing societal needs. The authors of this scoping review believe that developing sustainability studies can reconcile the strengths and weaknesses shown by the forty-year-old LTER-MC program so far. One option is implementing social–ecological studies that intend to define the Good Environmental Status (GES, [101]) and its changes in time based on the impressive background knowledge, long-term data availability, and multi-disciplinary fashion of LTER-MC, thus disclosing the potential of this time series in assessing the anthropogenic impact on marine ecosystems (UN Ocean Decade Challenge 2). One of the first examples of the latter aspect comes from the recently published manuscript by Romillac and co-authors, in which a multi-disciplinary team explored the interplay among anthropogenic impact, climate, and oceanographic forcing in driving the trophic state and phytoplankton biomass in the Gulf of Naples over the long term [91]. Similar studies are highly desirable in the next future.

Figure 7. The main words appearing in the LTER-MC aggregated topics Biodiversity (pink; **top**) and Phenology (light blue; **bottom**).

In addition, according to the UN Ocean Decade, integrative studies can generate knowledge to "innovate maritime economy under changing environmental, social and climate conditions" (Challenge 4), e.g., by predicting the effect of plankton community changes on fisheries and aquaculture. Even though the socio-economic importance of data from LTER-MC is still underrated, the local research community has recently become very active in collecting data in the Gulf of Naples and surrounding areas in the framework of the project FEAMP-ISSPA that is funded by the government of Regione Campania; this project is aimed at defining the GES based on the Marine Strategy Framework Directive (MSFD) and at investigating MSFD descriptors (https://environment.ec.europa.eu/topics/marine-environment/descriptors-under-marine-strategy-framework-directive_en, last time accessed on 9 August 2024) to inform policy-makers who manage local fisheries and aquaculture. The initial data from these surveys are now being published [64,102]). A primary value of LTERs stems from the "capacity development and equitable access to data, information, knowledge, and technology across all aspects of ocean science and for all stakeholders" (Challenge 9). In this latter respect, the LTER-MC community could take as a positive example what was done in other Italian LTERs that made their long-term data all FAIR (i.e., 'findable, accessible, interoperable, and reusable') and available to science, policy, and then to society [103]. Responding to challenges described above needs a close-knit, interactive, and open scientific community.

One must consider also that opening up a scientific community to society may be favored by increasing interactions with the non-scientific context; for instance, by engaging citizens in observing marine ecosystems, collecting samples, and taking scientific measurements while carrying out marine recreation (e.g., [104]). Even though the contribution of citizen or participatory science in LTER research is rising globally [105], such an approach has not been introduced in LTER-MC so far. Besides reducing the costs of monitoring, citizen science can make people more familiar with science, thus facilitating the transmission of scientific knowledge across society, a step urgently needed to build that capacity for a more sustainable economy in coastal communities [106].

In its 40-year life, LTER-MC has shown great resilience and adaptive behavior against potential threats, which could have underly the survival of this research. However, one must consider that a condition (and a threat) common to many LTER research studies is that they are costly and time consuming, and their value may become evident only many decades after their birth [107]. Nonetheless, in the course of their lifespan, to respond to scientific questions, LTERs acquire skills that become constitutive elements, such as the long-lasting expertise on specific topics. Unavoidably, some expertise attracts more funds for several reasons (see, e.g., funds related to harmful algal bloom species), become scientific assets, then exert a higher influence over the local scientific community, and eventually drive choices in the scientific coordination of a working group. This latter condition may threaten the *esprit de corps* needed for an LTER program to keep collective research as the momentum for conceptual integration, hampering the scientific innovation required to solve societal challenges [13]. Over decades, this weakness may limit the access to funds needed for an LTER to persist over time.

To sustain LTER research persistence in the Gulf of Naples for the upcoming decades, the authors of this paper remark on the need to counterbalance over-specialization, because it may generate thematic polarization, conceptual isolation, and resource concentration around a few topics, marginalizing ecology and weakening the trans-disciplinarity propaedeutic for the birth of new topics, as demonstrated by previous science policy investigations [16,17]. At the same time, one must consider that, on the one hand, holistic studies (i.e., focusing on the big picture) may undermine the attractiveness of observational, descriptive, and curiosity-driven studies in which the same holistic approach is rooted, while, on the other hand, more complex approaches, like omics, can shade the undisputable value of the observation of life forms in their environment ("ecology needs natural history", e.g., [99]).

As a final consideration, after analyzing objectively the scientific production of the 40-year-old LTER-MC, the authors of this scoping review suggest the scientific community grown around this latter research should pursue its intrinsic intellectual ingenuity, promote scientific openness, and stimulate collective research initiatives toward a good and financially opportune balance between basic and applied research, with the latter mainly oriented toward solving societal problems in an era of dramatic changes.

4. Conclusions

The 40-year-old LTER-MC research program represents an asset of the Stazione Zoologica Anton Dohrn in Naples. Its scientific productivity is copious, thematically wide, and scientifically inspiring, mainly at the level of basic research on plankton biodiversity in its multiple declinations in marine, coastal, and pelagic environments. The LTER-MC scientific corpus provided the knowledge background for functional studies ranging from biological molecules to ecosystems and from evolutionary to ecological processes, going beyond the specific site of observation. This latter perspective has arisen in the last decade and can fruitfully broaden LTER-MC's scope. In the very next future, the LTER-MC community could consider empowering its role in identifying environmental problems, informing coastal management, and supporting marine sustainability at the Mediterranean scale, as envisioned for marine observatories in the UN Ocean Decade (see, e.g., [108]).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/oceans5030034/s1, Supplementary Material S1: PRISMA Extension for Scoping Reviews (PRISMA-ScR) checklist. Supplementary Table S1: Bibliography analyzed with topic correspondence, modularity, and betweenness centrality values. Supplementary Table S2: Explanation of the labels used in Figure 5.

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