Unifying approaches to Functional Marine Connectivity for improved marine resource management: the European SEA-UNICORN COST Action

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Abstract

Truly sustainable development in a human-altered, fragmented marine environment subject to unprecedented climate change, demands informed planning strategies in order to be successful. Beyond a simple understanding of the distribution of marine species, data describing how variations in spatio-temporal dynamics impact ecosystem functioning and the evolution of species are required. Marine Functional Connectivity (MFC) characterizes the flows of matter, genes and energy produced by organism movements and migrations across the seascape. As such, MFC determines the ecological and evolutionary interdependency of populations, and ultimately the fate of species and ecosystems. Gathering effective MFC knowledge can therefore improve predictions of the impacts of environmental change and help to refine management and conservation strategies for the seas and oceans. Gathering these data are challenging however, as access to, and survey of marine ecosystems still presents significant challenge. Over 50 European institutions currently investigate aspects of MFC using complementary methods across multiple

research fields, to understand the ecology and evolution of marine species. The aim of SEA-UNICORN, a COST Action within the European Union Horizon 2020 framework programme, is to bring together this research effort, unite the multiple approaches to MFC, and to integrate these under a common conceptual and analytical framework. The consortium brings together a diverse group of scientists to collate existing MFC data, to identify knowledge gaps, to enhance complementarity among disciplines, and to devise common approaches to MFC. SEA-UNICORN will promote co-working between connectivity practitioners and ecosystem modelers to facilitate the incorporation of MFC data into the predictive models used to identify marine conservation priorities. Ultimately, SEA-UNICORN will forge strong forward-working links between scientists, policy-makers and stakeholders to facilitate the integration of MFC knowledge into decision support tools for marine management and environmental policies.

Keywords

conservation; ecosystem services; management; marine biodiversity; marine resources; marine spatial planning; meta-populations; meta-ecosystems

1 Introduction

Oceans and seas cover more than 70% of the Earth and deliver multiple ecosystem services, including some that shape human societies (e.g., food provision, climate regulation) (Food and Agriculture Organization of the United Nations 2018, IPBES et al. 2019). Moreover, marine resources already represent one of the largest economic assets in the world, and their value is projected to double by 2030 (Sumaila et al. 2021, OECD 2016). Sustainable management of the oceans and seas is, therefore, essential. Yet, marine conservation efforts lag far behind those of terrestrial habitats (UNEP-WCMC and IUCN 2021), with lower levels of protection (Sala et al. 2018, Claudet et al. 2020) and ineffective management (Bennett and Dearden 2014, Gill et al. 2017) compromising conservation outcomes. This had dramatic consequences so far. Indeed, marine ecosystems and resources are highly vulnerable to anthropogenic pressures, and most experience multiple, concurrent threats from local and global pressures (e.g., habitat loss, overfishing, pollution, warming and invasive species) (Halpern et al. 2015, Micheli et al. 2013, Gissi et al. 2021). Over the last century, the biomass of marine top predators has decreased by 90% (Myers and Worm 2003), and many coastal and oceanic habitats have been destroyed or severely degraded (Gubbay et al. 2016). Unprecedented losses in marine biodiversity are occurring, compromising the health of ecosystems (Cardinale et al. 201212). In Europe, 71% of assessed marine habitats are Critically Endangered, Endangered, Vulnerable or Data Deficient (Gubbay et al. 2016), whereas for the majority of species assessments the status of marine mammals, marine turtles, and fish stocks is ‘Unfavorable’ (European Environment Agency [EEA] 2015). Given the importance of marine wildlife and habitats to society and the intertwined fate of marine and terrestrial ecosystems, rapid and informed actions are needed to mitigate unwanted consequences of ongoing changes.

Planning sustainable development of the world's oceans requires a thorough understanding of marine biodiversity and its role in the healthy functioning of ecosystems. Gathering knowledge on marine connectivity is a crucial first step towards this, as it is needed to control the spread of invasive species, pathogens, and aquaculture escapees, construct effective networks of protected areas, conserve vulnerable taxa, and promote sustainable fisheries' management (Selkoe et al. 2016, Palumbi 2003, Beger et al. 2010). In ecology, connectivity refers to the movement of organisms, nutrients, and materials, and how those movements are facilitated (or not) by the landscape/seascape (Auffret et al. 2015). Therefore, connectivity assessments allow understanding relationships between the individuals, species or communities and the habitats or regions they inhabit. There are many divisions and subcategories of connectivity, which are often inconsistently defined and applied in ecological studies and management (LaPoint et al. 2015). However, the broad concept of 'connectivity' can be divided into two intertwined components (Tischendorf and Fahrig 2000): 'structural connectivity', a notion related to the physical characteristics of the landscape, and 'functional connectivity', which represents the response of organisms to environmental heterogeneity and structuring, encompassing their movements and exchanges between habitat patches. While human activities often result in changes in structural connectivity, it is functional connectivity that determines the demographic, ecological and evolutionary interdependency of populations and communities, as well as the flow of energy and organic matter among sites (Auffret et al. 2015). Hence, it modulates the ecological effects of environmental change, and ultimately seals the fate of species, ecosystems, and the services that they provide. Therefore, in order to predict how marine ecosystems will respond to future climate change, and to design effective conservation and management strategies, it is critical to build a more quantitative understanding of "Marine Functional Connectivity" (MFC).

Building this understanding is the central aim of the new European Cooperation in Science and Technology (COST) Action, 'Unifying Approaches to Marine Connectivity for improved Resource Management for the Seas" (SEA-UNICORN). This research network brings together a broad interdisciplinary community of scientists, stakeholders and policymakers, from more than 100 organizations across Europe and beyond (Fig. 1). Its purpose is to coordinate their research efforts and foster multidisciplinary interactions among them, to unify and integrate the varied approaches to MFC under a common conceptual and analytical framework for improved management of marine resources and ecosystems.

In this paper, we briefly list the major scientific challenges that this consortium aims to tackle, outline the theoretical and methodological advances expected from the COST Action, and present our strategy to advance the emerging field of MFC research and disseminate MFC knowledge in Europe and beyond.

2 Scientific challenges for the emerging field of MFC research

In the ocean, habitats and living resources are intrinsically interconnected. Yet, our knowledge on the spatiotemporal connections among them is still elusive and, as a result, connectivity at the community or ecosystem level is largely overlooked in decision-taking for marine management and policy (Balbar and Metaxas 2019, Barnes et al. 2018). Improving connectivity knowledge is key to ensure a sustainable Blue Economy in the coming decades. Indeed, all recent global initiatives for sustainable development, such as the Strategic Plan for Biodiversity 2011-2020 (Aichi targets), the 10 challenges for collective impact of the UN Ocean Decade 2021-2030 and the UN Sustainable Development Goal for 2030 n°14 "Life below water", require a comprehensive understanding of MFC and its drivers in order to anticipate environmental changes and their socio-ecological consequences. For example, accurate knowledge on current-day MFC and its likely evolution is needed to define operational conservation strategies for vulnerable species or ecosystems (Aichi targets 10 & 12), to accurately control the spread of invasive species, pathogens, or aquaculture escapees (Aichi targets 7 & 9), and to design optimal networks of protected areas (Aichi target 11). It is also required to ensure sustainable fisheries' management (Aichi target 6) and enhance the benefits derived from biodiversity and ecosystem services (Aichi targets 14, 15 & 16). The emerging field of MFC research can help answer all these societal needs. For this, it will have to rapidly and efficiently tackle the three major scientific challenges below.

2.1 Gathering operational MFC (and associated) data for protecting marine biodiversity

Given the spatiotemporal heterogeneity across marine habitats, an accurate and comprehensive knowledge of MFC is essential for making adequate decisions about where, when, and how to protect marine communities (Almany et al. 2009, Botsford et al. 2001, Magris et al. 2014). To improve the accuracy of MFC assessments, integrating methods is a key first step. Indeed, measuring or predicting MFC is challenging because, in the ocean, movements occur in three dimensions and few organisms remain sedentary across all life stages. Most marine species have at least one dispersal phase during their lifespan, typically at the propagule stage, but sometimes also at the juvenile or adult stages (Archambault et al. 2016). Describing their dispersive strategies is particularly challenging because of:

1. limited access to the marine environment,
2. typically small size of dispersers,
3. large population sizes, and
4. substantial dispersal distances, with no clear *a priori* relationship between life-history traits and dispersal potential (Pineda et al. 2010).

As a result, a diversity of methods and tools have been developed to predict, reconstruct or directly track organism movements among populations or habitats: most common are ecological niche modelling (Melo-Merino et al. 2020), biophysical modeling (Swearer et al. 2019), genetics (Selkoe et al. 2016), natural geochemical markers (Rooker et al. 2020), and physical tagging using acoustic (Donaldson et al. 2014) or archival tags (Rooker et al. 2019). Each technique has strengths and weaknesses that determine the type and accuracy of resulting MFC estimates, which in turn affects the potential for such data to inform management (Bryan-Brown et al. 2017). For example, genetic markers or other natural tags can provide sound evidence of connectivity, but the knowledge they provide with this matter is limited by the assumptions underlying their interpretation. Niche modelling and biophysical modelling can produce highly realistic predictions of species distribution and dispersal patterns at large spatial scales, but typically lack empirical validation, and often make assumptions that invalidate the results if violated. Finally, telemetry (physical tagging) can unambiguously identify individual movements but is often limited to larger organisms or life stages and provides only limited information on effective lifetime dispersal (Hart and Hyrenbach 2009).

During the last decade, technological developments across all these disciplines have generated major advances in MFC knowledge, which is now available for a broad range of aquatic organisms (from viruses to whales) and across all marine ecoregions. A significant bias towards organisms and areas that are perceived as important to society exists (Bryan-Brown et al. 2017), which will need to be corrected to get an accurate and comprehensive image of MFC, based on merged knowledge for a wide range of taxa, regions, and habitats. However, the greatest current impediment to broad scale MFC knowledge synthesis is the current lack of method integration (Bryan-Brown et al. 2017). Because methods differ in their underlying hypotheses and assumptions and/or the geographical or temporal scales they address, integrating them could lead to major scientific breakthroughs in marine research and policy. Indeed, this would allow filling important knowledge gaps that currently impede effective conservation of marine resources and ecosystems (Bryan-Brown et al. 2017). For example, the diversity in life cycle and lifetime migratory strategies within marine populations is likely to be far more common and complex than previously understood (Bradbury et al. 2008). Yet, it has been poorly studied so far (even for exploited species), so its ecological and evolutionary consequences are consistently overlooked in marine management. Similarly, whilst most marine populations could be connected by extensive propagule dispersal, self-recruitment is likely to be more important than previously thought (Berumen et al. 2012, Jones et al. 2009, Swearer et al. 2002). These patterns of diversity affect local population dynamics which, in turn, may affect evolutionary trajectories and modulate biodiversity at local and global scales (e.g., Durant et al. 2019, Ellingsen et al. 2020). Elucidating them within and among species, habitats and regions will require combining MFC data from complementary methods in a rigorous statistical way. However, to date, only a subset of methods has been combined (e.g., Pérez-Ruzafa et al. 2019), usually genetics (an inferential technique) with either natural tags (e.g., otolith composition, i.e., another inferential technique) or biophysical modeling (i.e., a predictive method). In contrast, other predictive methods (e.g., niche modeling) have never been integrated with empirical ones, such as tagging (Bryan-Brown et al. 2017, Hussey et al. 2015). Because of this, most of the published MFC knowledge relates solely to larval dispersal (60%), which has primarily been investigated to assess population structure (~48%). Only a small fraction of papers (0.5%) has been dedicated to higher-level ecological processes (e.g., material fluxes) and ecosystem services. This urgently needs to change if we want to produce MFC data allowing to match current conservation goals for the oceans and seas.

2.2 Producing adequate MFC (and associated) knowledge for preserving ecosystem function and services

Linking species distributions and movements to ecosystem function and services is key to enable sustainable blue growth. As organisms disperse or migrate (e.g., to reproduce or forage), they contribute to spatial flows of energy and materials that connect habitats and influence local ecosystem dynamics (Varpe et al. 2005). Importantly, because biologically mediated ecosystem functions (e.g., respiration and excretion) control most of the marine biogeochemical cycling (Welti et al. 2017), changes in species distributions, e.g., because of climate change or pollution, can impact nutrient cycling and sequestration (Pecl et al. 2017), affecting the overall functioning of the planet. The recognition of this link fostered the recent development of the meta-ecosystem theory, a powerful framework to predict the co-evolution of connected ecosystems (Loreau et al. 2003). However, empirical research in this field is progressing slowly, mainly because most approaches consider effective dispersal as the only type of organismal flows when many other movements can also connect ecosystems. Connectivity is inherently variable and dynamic, subject to intrinsic and extrinsic factors that affect the movements and survival of individuals (Treml et al. 2015). Documenting this variability and incorporating it into our understanding of meta-population and meta-ecosystem dynamics is very challenging (Gounand et al. 2018). Variations in biodiversity and in biogeochemical processes are just starting to be integrated into conceptual models, e.g., by modelling ecosystem services (Welti et al. 2017) but are crucial to understand and predict energy and material fluxes within and across aquatic ecosystems.

Valuable but undocumented information on the functioning of our planet is also embedded in the diversity of habitats frequented by particular species over their lifetime. Obtaining insights into MFC trends for key-stone taxa can thus be particularly valuable for decision-making in management and policy. For example, while microorganisms sustain key ecological functions (e.g., carbon cycling) and have a substantial economic impact on society (e.g., as human or animal pathogens), knowledge on their dispersal and distribution is very limited (Zhu et al. 2017). Another example is that of diadromous species, whose lifetime migrations contribute to the transfer of energy and matter between the continental and marine realms (Beger et al. 2010, Pérez-Ruzafa et al. 2020). Improving MFC knowledge of these species will help understand the spatio-temporal dynamics of coastal ecosystem services, allowing managers to optimize conservation actions both at sea and on land (Giakoumi et al. 2019). Fortunately, it is now within reach of MFC scientists to identify the processes that shape the microbial seascape and connectivity, especially as new methods such as metagenomics are available for this (Baker et al. 2021, Ininbergs et al. 2015). Theoretical frameworks and analytical tools to investigate connectivity within and among realms have also recently been developed (e.g., D'Aloia et al. (2017), Keeley et al. (2021), Zeller et al. (2018)), along with approaches allowing for integrated prioritization of conservation measures (Beger et al. 2010, Beger et al. 2015, Daigle et al. 2020). By building on these new frameworks and methodologies, future MFC research can shed new light on important ecological and economical linkages and provide mechanisms to incorporate this knowledge into management and policy.

2.3 Understanding MFC drivers & forecasting its evolution in the face of Global Change

Developing effective policies for sustainable ocean management requires a comprehensive understanding of present-day MFC and reliable projections of how it will evolve under differing global change scenarios. This can be achieved by identifying the past and present drivers of MFC. For example, habitat destruction and fragmentation during the 20th century resulted in significant loss of biodiversity because, when populations and communities become increasingly isolated, connectivity between them decreases (Lotze et al. 2006, McCauley et al. 2015). Similarly, changes in climatic conditions have modified the distribution of many marine species (Pinsky et al. 2020) and/or affected their reproductive or larval biology, leading to reduced connectivity and increased self-recruitment (Gerber et al. 2014, Munday et al. 2009). The ultimate consequences of the rapid environmental changes occurring in the oceans will depend on complex interactions between abiotic (e.g., temperature, habitat fragmentation) and biotic (e.g., physiological tolerance, interspecific interactions) factors, but also on the behavioral responses of resource users (Brierley and Kingsford 2009). Anticipating these effects relies on being able to accurately predict changes in species distribution (e.g., Cacciapaglia and van Woesik (2017)), ecosystem functioning (e.g., Boyd and Doney (2002), van der Molen et al. (2013)), and ecosystem services (e.g., Crossman et al. (2013)). However, to test hypotheses and improve projections, model parameterization requires high-quality, empirical, and relevant MFC data. Modeling also requires linking MFC metrics with physiological and biological requirements across species and life stages, in order to accurately predict behavioral, genetic, geographic, and demographic responses to environmental change.

3 The innovation and advances expected from the SEA-UNICORN COST

Many marine resources and ecosystems extend beyond geopolitical boundaries, and local threats to biodiversity can have impacts at local, regional, and international levels. Therefore, advancing MFC research requires networking and transdisciplinary cooperation at the international level. To this aim, the SEA-UNICORN COST Action (Fig. 2) aims to:

1. foster multidisciplinary interactions among the varied research communities involved in the study of MFC and the modelers that predict its ecological and economic consequences, and
2. consolidate their interactions with the stakeholders involved in environmental governance and sustainable exploitation for the seas, in Europe and beyond.

The Action extends over four years (2020-2024), and organizes various types of networking, collaborative and capacity building activities around the four main research coordination objectives below, each under the responsibility of a dedicated Working Group (WG). It will generate valuable new knowledge, both fundamental and applied, and facilitate knowledge transfer among research disciplines, end-users and countries, thereby impacting science, but also technology and varied social-economic sectors, in Europe and beyond. The vast network of MFC experts created has sufficient critical mass and complementary skills to drive international scientific and technical progress in MFC research in the coming years. It will strengthen Europe's research and innovation capacities, by facilitating international cooperation, and providing training and collaboration opportunities to spread scientific excellence in the field of MFC. These efforts will support the emergence of the 'next generation' of MFC scientists, with the robust multidisciplinary expertise needed for more comprehensive assessment of interconnections among populations, communities and ecosystems.

3.1 Objective 1 - Improve knowledge on MFC and its drivers (WG1)

MFC research is multidisciplinary by nature, relying on techniques ranging from field surveys to computer modelling, genomics and biogeochemical analyses. Due to the complex technical nature of these disciplines, the typical mechanisms for information exchange at the international level are not fully effective in the field of MFC. Indeed, it is highly unusual for individual scientists or research groups to be experienced in all of these disciplines. The complexity and diversity in terminology and methodology within each field impedes cross-disciplinary collaboration and makes it difficult for MFC scientists to stay informed of advances in other areas. This can lead to erroneous interpretation of MFC data and ineffective policy implementation. Gathering experts from diverse and global research teams into a single multidisciplinary network can therefore significantly advance MFC knowledge and generate invaluable contributions to both academic and applied spheres.

To this aim, SEA-UNICORN is establishing an extensive network of interdisciplinary and international connections among MFC scientists, in Europe and beyond. These researchers have started to combine their diverse and complementary expertise to critically evaluate the current state of knowledge on MFC (including at the sea-continent interface) and its evolution in the face of global environmental change. This will help identify key knowledge gaps and the taxa and geographic areas for which substantial information is already available. The consortium will also compile and compare MFC information from a wide range of taxa, ecoregions, and methods to highlight where coordinated research efforts would produce the most significant advances. In terms of science, it will create an unprecedented multidisciplinary approach to MFC research, and thereby lead to important conceptual and knowledge advances, not only in MFC science but also in diverse complementary research fields that investigate ecosystem functioning and evolution (e.g., biogeography, functional ecology, ecological stoichiometry). In particular, the Action will provide new insights into the role of MFC in the evolution of communities, ecosystems, and biogeochemical fluxes at sea and at the sea-continent interface, as well as into its importance for spatiotemporal dynamics of socio-ecological systems.

The primary innovation expected from SEA-UNICORN is methodological. While multiple research institutions are already attempting to address theoretical and technical limitations for effective MFC assessment, they still lack a universal framework to integrate multidisciplinary concepts and datasets in a statistically rigorous way. Multidisciplinary MFC studies so far have typically involved separate analyses by complementary methods (e.g., tagging and genetic markers in fish) and comparative interpretation of the results. Because of method limitations, such studies have typically been restricted to a single species or taxonomic group (e.g., fish and corals) and interspecific dependencies in MFC (e.g., the role of macro-organisms in the dispersal and distribution of microbes or parasites) are rarely considered (van Leeuwen et al. 2012). However, thanks to recent advances in Network Science, statistical frameworks now exist and allow simultaneous assessment of complementary descriptors, or integration of multiple, separate datasets (Jacob et al. 2020). SEA-UNICORN will build on these innovations to develop a theoretical and methodological framework allowing effective co-integration of complementary MFC data across disciplines (e.g., telemetry, genetic markers, and otolith fingerprints for fish), taxa and life-stages. This offers a promising avenue to improve MFC knowledge and enhance the usefulness and quality of the data collected by each discipline (Gaggiotti et al. 2018). For this, the Action will implement a platform for coordinated discussions to identify best-practice examples within each discipline and ways to facilitate data acquisition and integration, and to propose research projects to fill methodological or data gaps. Workshops and training schools will also be held to share multidisciplinary scientific and methodological expertise among the varied scientists currently involved in MFC empirical evaluation, promote research integration, and develop new MFC approaches that build on recent advances in analytical, statistical, and modeling tools. The ultimate goal is to provide a general conceptual and methodological framework that unifies concepts and approaches to MFC, allowing cross-disciplinary data integration and a more efficient use of resources at all levels (from sampling to science communication).

SEA-UNICORN will also innovate by producing new MFC descriptors, applicable to diverse taxa, regions and habitats, and encompassing the lifetime movements of marine organisms. The absence of such estimates currently impedes our understanding of the levels of interdependencies among species and ecosystems. Their production is essential if we are to predict the consequence of habitat and species loss at sea and anticipate the evolution of related socio-ecological systems. Comparing these standardized MFC descriptors among species will also improve our ability to extrapolate spatial connectivity at broader taxonomic (e.g., family, phylum) or ecological (e.g., guild, community) scales. The area of seascape genetics has already started to move toward this approach by gathering spatial information about meta-population structures worldwide, and genetic diversity changes at population, species, or community scales (Selkoe et al. 2016). We intend to continue and expand this effort, by collating and synthesizing MFC data across disciplines to generate generic descriptors of connectivity at ecological (e.g., species, guild, community) and policy-relevant (e.g., exploited stock, taxon, ecological compartment like benthos, etc.) scales. This is needed to progress from MFC patterns to processes, and to make use of MFC data to predict future changes in marine ecosystems and their socio-economic consequences.

3.2 Objective 2 - Incorporate MFC knowledge into forecasting (WG2)

Gathering effective knowledge to preserve ocean biodiversity and sustain marine ecosystem services (e.g., fisheries, climate regulation, tourism) requires combining MFC data with information on the ecological roles played by different species in the various habitats/ecosystems they inhabit. Unfortunately, MFC data are not yet adequately produced or referenced to allow this combination, which also precludes precise identification of the dependencies of ecosystem services and community livelihoods on marine biodiversity. To address this problem, SEA-UNICORN has started strengthening interdisciplinary interactions among the scientists involved in the evaluation of MFC and the modelers investigating its causes, its evolution and its ecological or economic consequences.

By providing unprecedented opportunities to bridge gaps between research fields, our aim is to foster MFC data use in marine biogeography, functional ecology, ecological stoichiometry, and socio-ecological systems science, and thereby contribute to the development of projection models that integrate MFC data (at sea and at the sea-continent interface) to predict the vulnerability of marine populations, communities, and ecosystem services to environmental change. To allow this, the consortium will foster the integration of concepts and methods between MFC scientists and complementary research fields. The network will also help to produce operational MFC data for use in the demographic, food web, ecosystem and stoichiometric models currently developed in the emerging disciplines of seascape genetics, spatial ecology, functional biogeography and ecological stoichiometry (e.g., Welti et al. (2017), Kadin et al. (2019)). For this, we will take advantage of recent theoretical and methodological advances in these research fields (e.g., circuit theory, Jacob et al. (2020), Moullec et al. (2019), Pastor et al. (2021)) to incorporate MFC data into models predicting trends in marine biodiversity, oceanic productivity, material fluxes and coastal socio-economics. This will greatly advance our understanding of how organisms drive ecosystem functioning, habitat characteristics and biogeochemical processes (and vice versa). For example, matching MFC estimates at the species, taxonomic group, functional guild or community scales with data on seascape and species distribution will allow linking organisms' movements to their physiological and biological needs, thereby providing unprecedented insights into the evolution of marine biodiversity. Combining them with data on species' ecological roles (e.g., trophic position) across life stages will help refine the ecological roles that organisms play in meta-ecosystems, both at sea and at the sea-continent interface. This will allow linking organisms' movements to their ecological function within marine and adjacent ecosystems, thereby yielding important new information about the influence of habitat use on species assemblages and matter fluxes at local and global scales.

3.3 Objective 3 - Produce relevant MFC data for management and policymaking (WG3)

MFC knowledge can inform local and regional management decisions and significantly improve global policymaking for the sustainable exploitation of the seas (Beger et al. 2015, Hidalgo et al. 2017). However, this requires MFC data to be generated in such a way that it can easily be incorporated into decision-making processes and decision-support tools for policy. Such straightforward integration is not yet possible. Despite the increase in the quantity and quality of the data and tools available on marine connectivity (Daigle et al. 2020, Hussey et al. 2015), connectivity is just starting to be incorporated in decision-making for spatial prioritization in marine management and policy (Balbar and Metaxas 2019, Barnes et al. 2018). Marine spatial prioritization that includes connectivity objectives typically relies on decision-support software to help decide the location of actions (e.g., establishing protected areas), while minimizing the conservation impact on resource users (Daigle et al. 2020). Over the last decade, an increasing number of metrics and frameworks have been developed to evaluate the connectivity across sea- and landscapes and guide the efficient allocation of conservation resources to areas identified as important for biodiversity (D'Aloia et al. 2017, Keeley et al. 2021, Zeller et al. 2018). However, their incorporation into common decision-support frameworks and tools remains technically challenging (Daigle et al. 2020). To build broad capacity in the marine ecology research community for including MFC knowledge into spatial planning processes, technical documentation, best-practice guidelines, and user-friendly tools are urgently needed.

Networking is the most effective approach to this challenge, as only direct interaction between MFC scientists and the diverse actors involved in marine (or littoral) management and policy will ensure that future MFC research meets societal needs. Supporting this goal, SEA-UNICORN will innovate by forging strong operational links between MFC researchers, socio-ecological system modelers, and the principal actors involved in marine policy and in the management of marine and littoral areas. Transdisciplinary collaborations will be fostered, and multiple training opportunities provided, aiming not only to familiarize MFC scientists with the specific needs of spatial management and policymaking tools, but also to initiate stakeholders to the methods providing MFC data relevant to decision-making. This approach will help decision makers understand the advantages and disadvantages of different methods and tools, allowing them to better apply MFC data to evaluate relevant management objectives. This capacity building will also promote appropriate data use by stakeholders and help MFC scientists plan their studies to generate datasets that can be more easily and effectively applied to decision-making at appropriate spatial scales. In particular, resource managers and policymakers with diverse expertise will be invited to actively partake in the COST Action, and to guide discussions that build on current advances in the development of decision-support tools that facilitate the integration of MFC data into management (Balbar and Metaxas 2019, Daigle et al. 2020, Keeley et al. 2021). These steps will ensure that future developments in the field of MFC are policy-relevant and needs-oriented and facilitate the compilation of datasets that can be more easily and effectively applied to decision-making (at the local and global scale).

Advancing the field of MFC research with this new integrated collaborative approach will encourage stakeholders to translate the improved MFC knowledge gained in the Action into fit-for purpose science. Through a cascade effect, we hope this will expand the range of end-users involved in the collection and utilization of MFC data. To this aim, the COST Action will provide a forum for dialogue between MFC scientists, policy-makers and the varied stakeholders implementing new marine management strategies. This will generate new collaboration opportunities between academics, policymakers and stakeholders that have hitherto worked in isolation on closely-related problems. This will also help national and international entities implement strategies that address urgent challenges to marine governance and management at sea, but also at the sea-continent interface. Indeed, given that MFC includes transboundary connections with freshwater, estuarine and coastal lagoon habitats, some of the data gathered will be of interest for stakeholders involved in the river basin and littoral management. The outcomes of SEA-UNICORN should thus be relevant for the implementation of the EU Integrated Maritime Policy (IMP), the Marine Strategy Framework Directive (MSFD), but also the Water Framework Directive (WFD) and the Habitats Directive (HD).

3.4 Objective 4 - Disseminating knowledge on MFC and raising awareness of its importance for a healthy planet and productive ocean (WG4)

The concept of 'connectivity' is recent and complex (Selkoe et al. 2016) and many marine actors and citizens still do neither understand its meaning, nor its importance for the maintenance of life and ecosystem services, especially at sea. One of the main ambitions of SEA-UNICORN is to significantly contribute to the transfer of knowledge from Academia to Society, by ensuring that the importance of MFC knowledge is widely acknowledged, not only by marine stakeholders and end-users (e.g. fishing communities), but also by the public at large. To promote global awareness about marine connectivity and its key role in the maintenance of ocean biodiversity and ecosystem services, knowledge on MFC and its role in ecosystem functioning must be transferred to a wide audience. This includes scientists and the wider public, but also varied types of stakeholders: national, supranational, and non-governmental organizations, coastal communities and national or local agencies involved in marine governance, and fishery or coastal management people. Adapting SEA-UNICORN's messages to these varied audiences is vital for efficiently spreading the results and importance of the topic.

To this aim, dissemination events will be organized to publicize the Action and its outcomes to relevant international communities of scientists and stakeholders. The knowledge and methodological insights gained over the course of the Action will be disseminated to the research community through the joint production of open access peer-reviewed publications. The MFC data compiled or generated by the Action participants will also be added to databases of recent initiatives aimed at describing global patterns in species connectivity (e.g., migratoryconnectivityproject.org, mgel.env.duke.edu/mico, icarusinitiative.org). SEA-UNICORN further aims to produce guidelines for scientists to help them optimize the quality and value of the MFC data they produce, and white papers for incorporating different types of MFC data into marine management and environmental policymaking via decision-support tools. Building on the extensive expertise gained from recent COST Actions aiming at bridging the gap between science and policymakers in Europe (e.g., OceanGov and MarCons), we will ensure that the white papers produced by SEA-UNICORN are useful for relevant target audiences and disseminated through the appropriate channels. This will help bridge the gap between policy and science, and catalyze the implementation of research-based policies in Europe and beyond. Given the international scale of this COST Action and the relevance of its outcomes for mitigating climate change effects and optimizing global environmental governance, the UN Environment Agency (UN Environment, in particular the Mediterranean Action Plan), the Food and Agriculture Organization (FAO), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and several international non-governmental organizations (e.g. IUCN, WWF, Oceana) will be some of the targets for dissemination.

SEA-UNICORN will also ensure that the scientific information produced is effectively communicated to a wide audience of stakeholders and end-users. For wider and more active dissemination and discussion, social media networks (e.g., Twitter, LinkedIn, ResearchGate) will be used. Press releases will be made to publicize the Action and its outcomes across multiple media outlets, and varied educational visuals (posters, leaflets, comics, videos, etc.) on MFC will be produced. Finally, to promote global learning on MFC, a Massive Open Online Course (MOOC) will be produced to be hosted by a non-profit open-source educational platform (e.g., fun-mooc.fr).

4 Concluding remarks

The increasing pressures on marine biodiversity and the drivers behind these pressures cannot be effectively managed until the complex, dynamic ecosystem-level changes at sea are better understood (Halpern et al. 2015). Improving worldwide knowledge on marine connectivity is a crucial first step towards filling this knowledge gap, since it will improve our ability to preserve marine and coastal ecosystem services and promote species and habitat resilience to global change. Fit-for-purpose MFC science and data are urgently needed to inform marine policies to support the sustainable development goals for a well-functioning ocean described in the 2030 Agenda of the UN Decade of Ocean Science for Sustainable Development (https://www.oceandecade.org). Given the short time remaining for adapting to ongoing environmental changes at sea (IPBES), there is an urgent need to take a holistic approach that synthesizes previous work alongside ongoing studies in order to catalyze new understanding and inform marine policy development.

The SEA-UNICORN COST Action is particularly timely as it will facilitate pioneering theoretical and methodological advances in varied disciplines, using them to revisit concepts and approaches in MFC research and unify them under a universal and policy-oriented framework. The Action will also provide a structured setting for MFC scientists to learn about advances in other disciplines, and for scientists and stakeholders to debate and work together. This will enhance conceptual and methodological understanding among disciplines and enable cross-fertilization of ideas and development of robust research protocols and policy procedures. This will significantly improve our understanding of MFC and stimulate the emergence of a more systematic and outcome-focused research field, matching the needs of national and international managers and policymakers, and helping them to identify strategies for sustainable management, at sea and the land-sea interface. Besides the technological and scientific innovations expected from its large consortium, this initiative will promote capacity building among marine scientists, managers, and policymakers, within and outside of Europe. It will also strengthen global public awareness and understanding of the importance of protecting marine life and its diversity to preserve the functioning of our planet and secure the future of our societies. The multifaceted activities across the Action will help to bridge the gap between science, policy, and society, and contribute to the challenge of halting the loss of biodiversity and productivity in the European and contiguous seas.

Acknowledgements

This article is adapted from the MoU of the COST (European Cooperation in Science and Technology) Action CA19107 ‘Unifying Approaches to Marine Connectivity for improved Resource Management for the Seas” (SEA-UNICORN) - supported by the Horizon 2020 framework programme for research and innovation.

Grant title

COST Action CA19107 ‘Unifying Approaches to Marine Connectivity for improved Resource Management for the Seas” (SEA-UNICORN) - https://www.cost.eu/actions/CA19107/

Conflicts of interest

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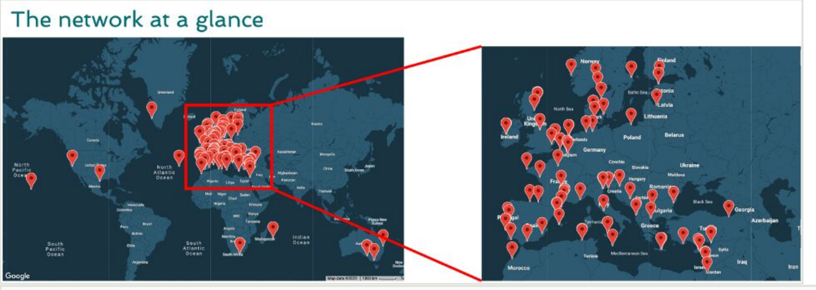

Figure 1.

Location of the organizations in the network of the COST Action SEA-UNICORN with a focus on the researchers working on the European Seas (date: 01/08/2021).

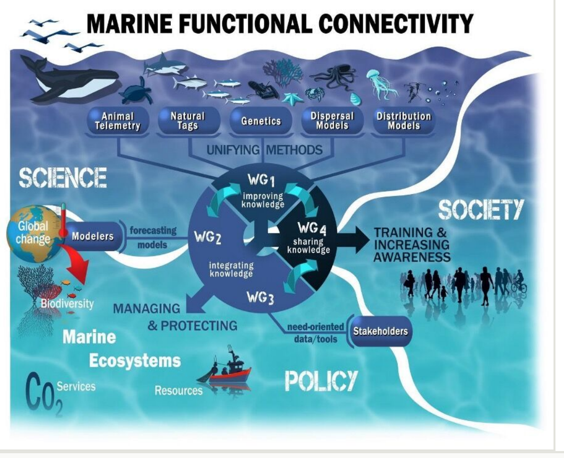

Figure 2.

General structure of the SEA-UNICORN COST Action, in link with its objectives and expected outcomes at the Science-Policy-Society interface. WG = Working Group.